Development of a Fish Acoustic Buoy and Underwater Logging System (FABULS) Passive Acoustic Recorder for use in surveying responses of coastal fishes to hypoxia and anoxia

A Final Report Submitted to

The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET)

Proof of Concept Program

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Oct 31, 2005

This project was funded by a grant from NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology, NOAA Grant Number: NA04NOS4190109

Introduction

Monitoring the use of essential fish habitat and how it is affected by hypoxia in estuaries is a growing concern (Seliger et al. 1985), because poor water quality conditions can constrain fish population growth and reproduction (Stanley 1992). In Pamlico Sound and other NC estuaries used by drum fishes (Sciaenidae), summertime hypoxia is a regular event that causes fish kills and changes the distribution of fish and crabs (Stanley and Nixon 1992, Paerl et al. 1998). The availability of suitable habitat for these estuarine-dependent fish and invertebrates are thus reduced, thus affecting the fishing industry and recreational users. To combat hypoxia, the NC legislature has enacted a nutrient reduction plan with a target of 30% reduction in nitrogen input to these watersheds. As the nutrient reductions are implemented, the hypoxic conditions in these estuaries will be monitored using data-logging water quality and dissolved oxygen meters. However, there is a need to study, simultaneously with improvements in water quality, the distribution of fishes as a response to hypoxia. As the estuaries are restored to conditions that reduce hypoxia, managers need to demonstrate that fish abundance is returning to normal levels. Monitoring fish abundance is a difficult activity, fraught with difficulties ranging from gear avoidance by the target fish species to high labor and vessel costs, which result in intermittent sampling. Worse, the sampling of fish stocks often does not occur at a frequency that allows one to study the response of fish to short-term hypoxic events.

We have been successful in devising a continuously sampling autonomous sonobuoy for fish passive acoustic research (Luczkovich et al. 1999, 2000). Our original sonobuoys recorded fish sounds for 90 s on analog tapes at intervals of ½ hour to 1 hour automatically during a single night, and were deployed over the course of a year at various locations in Pamlico Sound, NC. A small boat was used to deploy and recover 10 sonobuoys at randomly selected sites within two grids on a daily basis and the sound was surveyed biweekly for a summer in 1998. The sonobuoys recorded the activity associated with spawning in these areas during 24-hour periods. With this system we successfully recorded the sounds of weakfish, spotted seatrout and red drum, three commercially and recreationally important species that spawn in estuaries in NC in the summer. However, the sampling was limited to 24-hour periods in this version due to the limitation of recording on analog tapes.

During the summer of 1998, we noticed that the sound production from weakfish and spotted seatrout decreased with increasing hypoxia. The correlation between *Cynoscion* drumming index and bottom dissolved oxygen concentration measured the next day at each sonobuoy location was positive (Pearson's $r = 0.29$, Bonferroni $P = 0.00043$). In fact, the lowest levels of fish drumming occurred when dissolved oxygen levels fell below 4 ppm during the middle of the summer. Thus hypoxia, a common summer time event in Pamlico Sound that is exacerbated by anthropogenic nutrient input from the Pamlico and Neuse Rivers, seems to cause a decline in spawning in these two sciaenid species. It is not understood how this hypoxia is affecting the spawning of sciaenids in heavily polluted estuaries, the National Estuarine Research Reserve System, or in recovering estuaries. A cost-effective monitoring system that can be deployed nationally to continuously monitor the effect of hypoxia on fish spawning is required.

We have developed a new all-digital system for recording sounds (Fish Acoustic Buoy and Underwater Logging System or FABULS) that interfaces with water quality meters (YSI Model 6600 Data Sonde) already installed at most National Estuarine Research Reserves. This new digital passive acoustic monitoring system will allow researchers to simultaneously monitor the acoustic environment and the water conditions at multiple locations in an estuary, allowing managers to determine extent of the hypoxia affecting spawning. In recovering and restored estuaries, researchers will be able to monitor improvement of the hypoxia and spawning activity to test the effectiveness of management and estuarine restoration actions.

A prototype was tested at the Rachel Carson National Estuarine Research Reserve (NERR) in North Carolina. This system is consistent with the goals of the NC Estuarine Research Reserve, which are to identify and track long-term changes in the status, integrity and biological diversity of estuaries. During our study, on selected deployment tests, the FABULS and a YSI water quality meter were deployed within the Rachel Carson NERR to sample salinity, water temperature, pH, turbidity, dissolved oxygen, conductivity, and depth. The FABULS system will add the dimension of real time monitoring of fish habitat use and the correlation of the water quality data and the passive acoustic data.

Objectives and methods

Our primary objective was to develop and test a FABULS system that would work with existing water quality data loggers used at the NC Rachel Carson NERR. We constructed the monitoring device for monitoring the acoustic behavior of the Sciaenidae and other soniferous fishes in estuarine systems with a dissolved oxygen, salinity and temperature data sonde. The system consists of an ultra low-power computer (Arcom Viper PC104 400 Mhz with Intel PXA255 RISC Processor) with 1.6 W power consumption (or 0.2 W in standby mode) running a Linux operating system and a large (2GB) compact flash card (Figure 1), and uninterruptible power supply (UPS, Arcom Viper UPS) and a 12-V sealed lead-acid battery. The computer has an onboard SDRAM file system, 5 serial ports, 2 USB ports, audio card, and measures 96 mm x 91 mm. The power supply converts the battery output to a constant 5 V required by the computer. The computer, power supply, and battery are enclosed in a plastic underwater housing (Ikelite 5800, Figure 2). The housing has two bulkhead connecters (Figure 3, SubConn Model micro3 for a low-frequency hydrophone HTI model 96-min and micro8 connector for the serial connection with the YSI 6600 EDS water quality meter). Prior to deployment, the FABULS is started by connecting battery power, connecting a laptop computer to the internal serial connection, and using a serial terminal emulation program, such as Hyperterminal on Windows XP to set sampling parameters. This is done by logging onto the computer and executing a setup script which sets the system time/date and prepares the computer for deployment. Finally, the housing is closed, the hydrophone and data sonde cables are attached to the housing bulkhead connectors, and the data sonde and housing placed in a deployment frame (Figure 4).

The hydrophone recorded the ambient sounds at programmable intervals (10 s recording every 15 min) while simultaneously recording the temperature, salinity, turbidity, depth, and dissolved oxygen concentrations at the deployment site. Sound files were digitized at 22 kHz and stored as Windows WAVE sound files on the Compact Flash card. The 2 GB Compact Flash card allows the storage of more than one month's worth of audio and water quality samples. Battery capacity is the limiting factor for the system, though. At the current time, the rechargeable sealed lead-acid 5 A-h battery lasts 55 hours during each deployment before exhaustion. We replace and recharge batteries when we recover the unit, but we are working on extending battery life by adding a solar panel for recharging. Additionally options for extending the deployment time include completely powering down the computer between samples (using a timing circuit to trigger restarts) and using larger capacity batteries. YSI dissolved oxygen probes require service on a monthly basis, so our goal is to extend the FABULS recording life to 30 days. Based on our previous knowledge (Luczkovich et al., 1999), we can sample more intensively after dark when fish are calling and less intensively during the day when they are inactive to save on disk storage and extend battery life. The sampling schedule is under complete control of the programmer by setting a series of software switches at start-up and deployment.

Results

The development and construction of the FABULS was no small task. In addition to building and wiring the device, we had to write the software that controls the system. The ECU Electronics Shop assembled the internal electronics and designed the hydrophone power supply. The ECU Physics Instrument Shop constructed the internal frame, which holds the components inside the waterproof housing, and also the external frame for the FABULS and YSI sonde.

A large part of the development of the FABULS was writing the controlling software. The Viper computer runs a Linux operating system (Linux kernel version 2.6.11.9). We wrote custom programs to record sound, query the YSI sonde, control system sleep (low power mode)/wakeup, and to configure the system for deployment. Where possible, our custom software is based on modified open-source programs available for Linux computers.

We overcame several software development obstacles that are expected when building a new device. In order to wake the system from sleep at a pre-set time, we had to configure the computer to use the auxiliary hardware clock. To accomplish this, we had to upgrade the Linux kernel (to version 2.6.11.9). This upgrade required us to change the way our sound-recording software accessed the audio card. Troubleshooting each of these issues was time-consuming, but we were able to develop software that records acoustic and water-quality samples reliably.

Another task was to develop a deployment protocol to minimize the chance of deployment errors. We fine-tuned this protocol through trial and error. There are several connections and settings necessary for the FABULS to function properly, and a single mistake could result in failure to retrieve data. A deployment procedure with a checklist, detailed below, minimizes the chance of setup errors.

FABULS Deployment Checklist

1. Recharge the battery.
2. Insert the Compact Flash card into its slot on the Viper computer.
3. Secure the battery in the battery holder inside the housing.
4. Connect FABULS COM1 port to a laptop computer with a serial connection and run a serial terminal emulation program (such as Hyperterminal or C-Kermit) on the laptop.
5. Connect the FABULS power supply cord to the battery and allow the Linux system to boot.
6. Log on to the FABULS (using the terminal emulation program) and run the setup program by entering the command "setup" (without the quotes) at the prompt.
7. Follow the directions given by the setup program to set the system time/date and the initial sleep before the first sample.
8. Disconnect the laptop serial cable and close the waterproof housing.
9. Place the FABULS and the YSI sonde in the external frame and tighten the connector screws.
10. Connect the YSI serial cable to the YSI sonde and to the FABULS. Check to make sure both connections are secure.
11. Connect the hydrophone cable to the FABULS. Check to make sure that the connection is secure.
12. Use cable ties to secure the hydrophone to the frame and to secure excess cable inside the frame.
13. Attach the float line to the frame.
14. Lower the frame into the water until it rests on the bottom.
15. Record the deployment site information including latitude and longitude, water depth, and (where possible) water quality readings.

Discussion

One advantage of the FABULS is its programmability. The Viper computer can be programmed to sample on a complicated schedule and even to interact with a variety of instruments. For example we have already programmed the FABULS to interact with a Hydrolab sonde to obtain water quality measurements. Also, the computer can be programmed to perform complex data processing, including spectral analysis, to reduce the raw data to a smaller summary report that can be transmitted to the laboratory via a modem (cellular, radio, satellite, etc.).

Next Steps/ Future Research

The FABULS data recorder is now fully operational, and the preliminary results indicate that the system should be produced and deployed on a much larger scale. The device records acoustic activity along with water quality variables, but we cannot answer the larger question of the relationship between water quality and acoustic activity with a single unit deployed for a short time. Long-term deployments of multiple units are necessary to address this issue.

Currently, the deployment time of the FABULS is limited by battery capacity. The 12 V, 5 A-h batteries that we used to power the system last about 55 h before they become discharged. We can extend this deployment time by increasing the battery capacity and by making the FABULS more energy efficient. We are working to implement both of these strategies in the next-generation device. There are several ways to make the unit more efficient. A typical deployment involves taking four recordings (of both sound and water quality parameters) each hour. The FABULS requires approximately 2 min to make the recordings (including waking from sleep, making a 10-s sound recording, allowing the YSI sonde to warm up, and recording the water quality readings). This means that the FABULS is active for 8 min and in sleep (low power) mode for 52 min each hour. Clearly, reducing the power used during system sleep could significantly extend the deployment time. The latest Viper computer reduces sleep mode power by approximately 50% over the model we used in the FABULS. We could further reduce energy consumption between recordings by turning the computer off completely. We are developing a low power microcontroller circuit that will turn the Viper computer on after a programmed interval, allowing it to boot, make a recording, and shut down. The power used during the powered-down time would be limited to the microcontroller power (~2 mW compared to 250 mW in sleep mode). We can possibly reduce the power used when the FABULS is active (awake) by turning off all unnecessary hardware (i.e., the Ethernet and USB interfaces) and by reducing the processor clock speed (downclocking). The disadvantage of downclocking is that any data processing programs implemented in the future would take more time to run. Finally, we could reduce the energy consumption by optimizing the time that the device spends in active mode. The DO sensor on the YSI sonde requires approximately 60 s to warm up after an inactive period. The FABULS warms up the sonde by making several discreet samples during a 60-s interval. One way to improve on this method would be to place the sonde in unattended mode programmed to sample just before the FABULS activates to make a recording. Then, the FABULS could simply obtain the latest sonde measurement rather than waiting for a 60-s warm-up. Another possibility is to use a sonde with a DO sensor that does not require a warm-up period. Reducing the DO probe warm-up time in this way would reduce the active time by about 50 s.

An obvious way to extend deployment time is to use a higher-capacity battery. We selected the 12 V, 5 A-h battery because it fit inside our Ikelite waterproof housing. A higher capacity battery would be too large to fit. The next-generation FABULS will include an additional connector so that the unit can use an external battery (or other energy source). We are investigating the use of a battery/solar cell combination for extended deployments.

If yes, briefly describe the objectives of potential future research.

The FABULS has potential for future research. One limitation of many ecological studies is that the inability to make simultaneous measurements in multiple locations. Deploying multiple FABULS units will allow us to do just that. We will be able to compare simultaneous acoustic recordings and water quality data at several locations and times within a study area, allowing us to have both spatial and temporal resolution. We will be able to address questions about whether the sound levels decreased because the fish stopped calling or whether they moved to another location. This question and many others are impossible to address with single point samples.

Another possibility for future research is an extended deployment of the FABULS. Long-term deployment would allow us to determine the day-to-day variability of the acoustic activity and allow us to relate that to water quality parameters. Right now, we are working on a system with a solar battery charger and a radio modem. The unit will send data to an on-shore base station, which will relay it to the laboratory. Such a system could be deployed for up to two weeks between maintenance visits. This deployment time is limited by the maintenance required to clean the fowling from the YSI sonde.

Based on the results of the research is there an applied tool that could be developed to address a specific coastal and estuarine issue?
If yes, please describe the management issue or problem and how coastal managers might use the tool.

Figure 1. The schematic diagram of the FABULS showing the Viper computer, with compact flash (CF) card for storage, inputs from the hydrophone and YSI water quality sonde, battery and uninterruptible power supply (UPS).

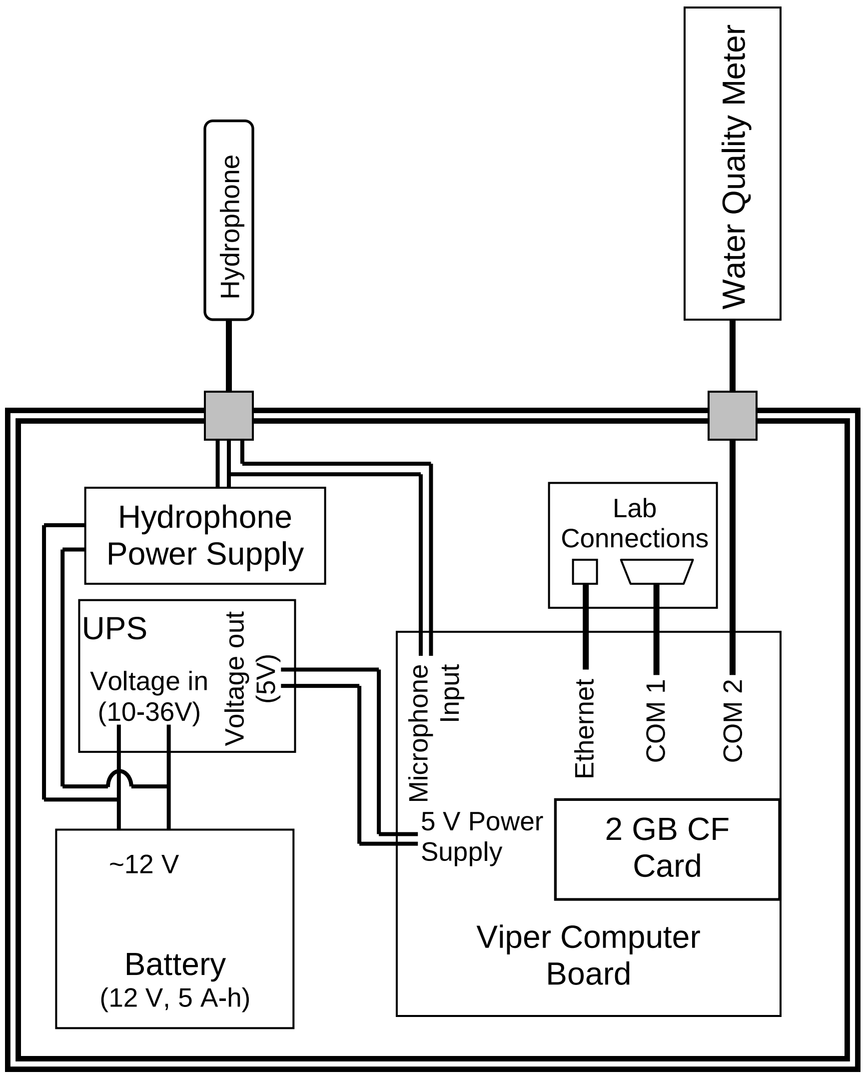

Figure 2. Photos of the FABULS in laboratory, pre-deployment. The Ikelite housing (foreground) contains a rechargeable sealed lead acid 5 amp-h battery with supports to hold the battery in place. The Viper computer and UPS are mounted to the housing's lid (background), with internal connections for power, serial and Ethernet cables. To set-up and program the Viper, the power cable is connected to the battery leads and a laptop computer is connected to the internal serial port. A red reset button is present for resetting the computer during pre-deployment procedures.

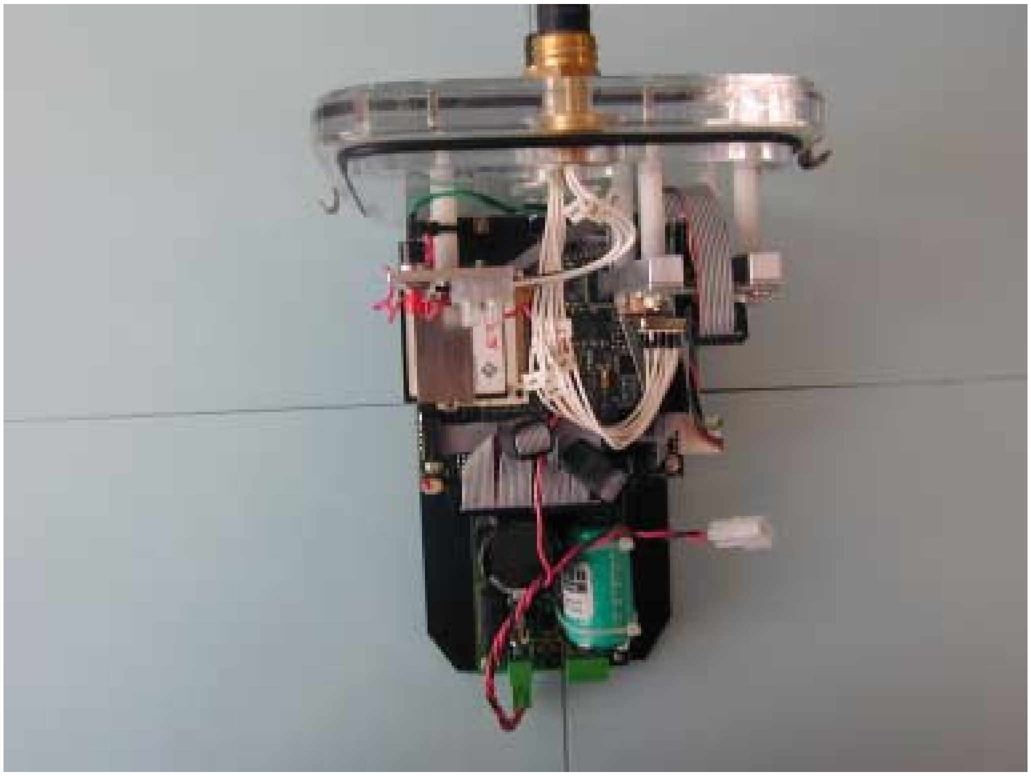

Figure 3. Top view of the FABULS, out of the housing, with the lid and internal wiring visible. The removable compact flash card used for data storage is visible on the upper left of the computer, just below the reset button. The underwater bulkhead connectors are at the top, penetrating the lid of the housing. The power connector is at the bottom right.

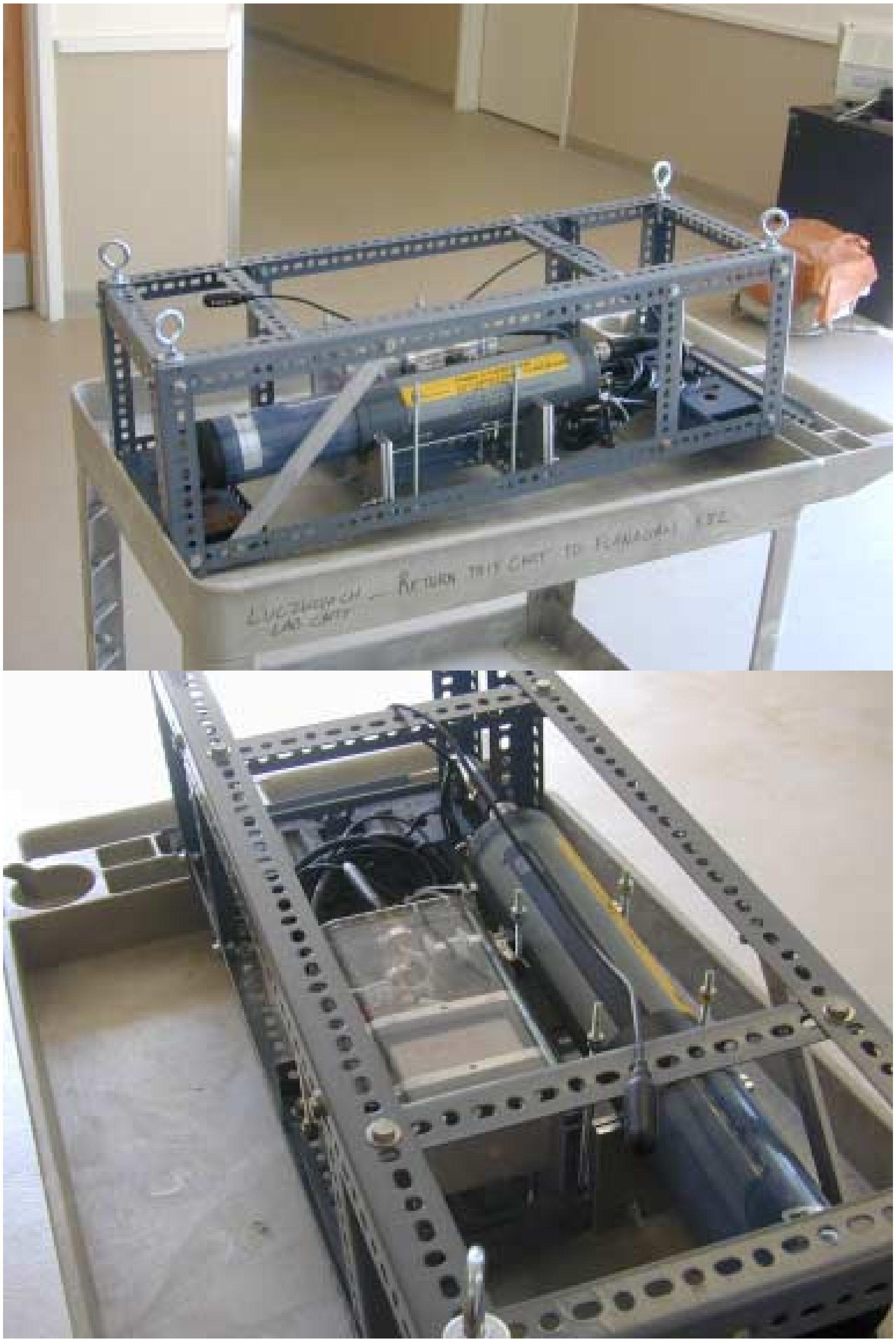

Figure 4 (top and bottom). Top – the deployment frame with YSI data sonde and FABULS housing. Bottom – an end view of the frame, showing location of the FABULS and sonde, with HTI hydrophone at top. Prior to deployment, angle iron clamps and cable ties are used to secure the housing, sonde, and hydrophone to the frame. The frame is weighted and a marker float is attached prior to deployment.