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PILS: Low-Cost Water-Level Monitoring

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1. Introduction

The estuarine environment is important both to global ecology and to human economy. Estuaries are the place where freshwater meets saltwater, and so they typically contain a bounty of marine species, and are essential to the life cycle of many marine organisms. For similar reasons, they often contain sea ports and carry commerce of great value.
In order to study estuaries in more detail, we have developed two sets of low-cost sensors using off-the-shelf technology combined with innovative new low-cost circuits. The first, nicknamed "Jag Ski", is a highly mobile water craft for navigating estuarine and littoral areas and providing real-time data. The second, named "PILS", is a network of stationary sensors for making long-term water-level measurements. This paper describes the construction of both, along with actual measurements.

2. Survey of literature

Sensing the environment can be carried out through remote measurements (e.g. satellites (Villa & Gianietto, 2006)) and through in situ measurements (e.g. wireless sensor networks (O'Flyrm et al., 2007; Thosteson et al., 2009)). Both have been demonstrated successfully as means of measuring characteristics of water.
An example of one real-time water-sensor architecture is the Land/Ocean Biogeochemical Observatory (LOBO) system developed by Satlantic and the Monterrey Bay Aquarium Research Institute (MBARI) (Comeau et al., 2007; Jannasch et al., 2008) and has been installed in the field (Sanibel-Captiva Conservation Foundation, 2009). Others include the Ocean Observation Initiative (OOI) (Frolov et al., 2008; National Research Council, 2003; U.S. Commission on Ocean Policy, 2004), NOAA tide gauges for storm surge (Luther et al., 2007), and sonar-based water-level measurements (Silva et al., 2008). Specific to environmental monitoring in the coastal ocean, mobile field assets typically include profiling floats (Roemmich et al., 2004), autonomous underwater vehicles (AUVs) (Rudnick et al., 2004), and unmanned underwater vehicles (UUVs) (Freitag et al., 1998; Frye et al., 2001).
This work is in line with these earlier systems. We have adapted the mobile sensor platform to a highly maneuverable manned platform to navigate shallow-water areas proficiently. The sensor network is designed for relatively low cost and for unattended measurements. It also contains novel sensors for pressure and salinity.

This work is motivated by the fact that computer models of estuaries need refinement. For example, there is disagreement whether wind forcing or river discharge dominates the dynamics of Mobile Bay (Schroeder & Wiseman, 1986; Kim et al., 2008). Data obtained using the sensors will be used to parameterize a linear approximation of a static momentum balance of the estuary (Van Dorn, 1953) to improve simulation and forecasting accuracy.

3. Real-time monitoring: Jag Ski

The University of South Alabama Jag Ski is a three-person Kawasaki Ultra LX personal watercraft (PWC) equipped with state of the art instrumentation developed by YSI, Incorporated, SonTek, VarTech Systems, and others (Fig. 1). In addition to the PWC, a Kawasaki Mule 3010 four-wheel drive utility vehicle can be used for launching and retrieval when a proper boat launch is not available. The Jag Ski contains an onboard small-form PC running the Windows XP operating system, a foldable waterproof keyboard, a fully submersible touch screen LCD display, and four dry-cell 18 amp hour, 12 volt marine batteries to supply enough dedicated power for twelve to fourteen hours of data collection. The PC, power supply, and other assorted equipment are housed in waterproof cases with internal foam padding. All external cabling and bulkhead connectors are fully submersible. Experience has demonstrated that items labeled water resistant and waterproof offer little protection in the corrosive, marine environment.

Fig. 1. The South Alabama Jag Ski and 4x4 towing vehicle.

The use of PWCs for collecting hydrography is not a new idea. There are numerous examples of PWC systems around the country (and world). Some of the earlier successful applications are discussed in (Dugan et al., 1999; Dugan et al., 2001; MacMahan, 2001; Puleo et al., 2003). The PWC has also successfully been used for larval fish sampling in shallow waters (Strydom, 2007). More recently, however, Hampson et al. (2011) have demonstrated the skill of using a kayak as a surveying platform for still shallower survey applications.
What perhaps makes the Jag Ski so unique in the context of PWC hydrographic data collection systems is its suite of instrumentation. Prior to the Jag Ski, the use of the PWC has been mostly limited to bathymetric surveys in nearshore waters. While it certainly has its limitations, the ability of the PWC to traverse the surfzone in hydrographic surveying cannot be rivaled by most traditional vessels. The addition of a PWC to one's hydrographic surveying deployment provides a very good overlap between land-based surveys and those conducted in deeper waters using traditional watercraft. The Jag Ski, however, was

developed to meet broader goals and objectives in the area of coastal, water resources, and environmental engineering.

The Jag Ski contains a SonTek/YSI RiverSurveyor M9 Acoustic Doppler Current Profiler (ADCP) with an integrated Real Time Kinematic Differential Global Positioning System (RTK DGPS) for georeferenced measurements (Fig. 2). The M9 ADCP has a profiling range of 6 cm to 40 m, and is capable of measuring velocity magnitudes up to 20 m/s. The resolution of the velocity measurements is as low as 0.001 m/s, and vertical bin sizes can be as small as 2 cm, or as large as 4 m. The horizontal resolution of the samples is a function of the reported sample rate (generally 1 Hz) and vessel speed (preferably equal to or less than the water velocity). A nominal speed of 1 – 2 m/s is maintained when using the M9 ADCP on the Jag Ski, so a typical horizontal resolution is, accordingly, 1 – 2 m.

Fig. 2. SonTek/YSI RiverSurveyor M9 ADCP and RTK DGPS base station.

The M9 ADCP contains a dedicated 500 KHz vertical beam for depth measurements and bottom tracking, four slanted 1 MHz beams for sampling in deeper water, and four slanted 3 MHz beams for sampling in shallower waters (Fig. 3). This dual-frequency functionality is unique in the ADCP market, and along with its integrated GPS system for vessel-corrected measurements to account for the moving reference frame, makes it attractive for applications in Mobile Bay (Fig. 4). The bay is a broad, mostly shallow (< 4 m), drowned river mouth estuary that is incised by a navigation channel dredged to a maintenance depth of about 15 m. The depth of the channel in the main entrance to Mobile Bay can reach 20 m or more, and is flanked to the west by a broad, shallow area with depths less than 3 m. The dual frequency M9 ADCP performs well when transitioning between the two extremes.

Aside from the technical capabilities of the RiverSurveyor M9 ADCP, the instrument comes with a well-developed, integrated software package for setup and data collection. The RiverSurveyor Live (RSL) software is loaded on the onboard PC, and is fully interactive using the touch screen LCD display. Some very helpful features of the software include dynamic icons that quickly report the status of various systems, like GPS and bottom tracking, the ability to see a real-time estimate of discharge, and the integrated GIS shapefile functionality for easy navigation and spatial awareness.

Fig. 3. SonTek/YSI RiverSurveyor M9 ADCP head.

Fig. 4. Terra/MODIS imagery of Mobile Bay taken November 8, 2002. Image courtesy: NASA Visible Earth.

The initial research focus for the Jag Ski was fulfilled with the integration of the RiverSurveyor M9 ADCP. That one piece of equipment provides the capability to perform detailed beach profile surveys, detect and image scour holes near bridge foundations, and measure the spatial variability and magnitude of coastal and nearshore currents, as well as riverine flows. And as preparations were being made in April 2010 for upcoming field experiments in coastal Alabama during the months May – August, the explosion and subsequent sinking of the *Deepwater Horizon* drilling platform later that month unveiled a new, and unexpected, application for the Jag Ski: environmental monitoring.

The National Science Foundation (NSF) issued a number of awards for research, instrument acquisition, and instrument development related to the 2010 Gulf Oil Spill through their RAPID program in the months following the initial explosion and sinking of the platform. The Jag Ski received one such award, issued through the NSF Major Research Instrumentation program. The purpose of the award was to purchase an instrument that could be used to measure near-surface water quality parameters, as well as crude oil and refined fuels, in Alabama's coastal waters. The result is a rather unique piece of equipment produced by YSI, Inc. called a Portable SeaKeeper 1500 (Fig. 5). The Portable SeaKeeper, or PSK, is a scaled-down version of the SeaKeeper 1000 systems that are deployed on nearly 50 different vessels of opportunity around the world. Some vessels are used for research, others are operational ferries, and still others are private yachts. Each of these vessels contributes data and research to the International SeaKeepers Society, and now the Jag Ski does, too (Fig. 6).

Fig. 5. The YSI Portable SeaKeeper 1500 mounted on the stern of the Jag Ski.

Fig. 6. Initial testing of the YSI PSK on a local river.

The PSK contains an YSI 6600v2 sonde, a Turner Designs C3 submersible fluorometer, a Thrane & Thrane Sailor Mini-C vessel monitoring system, a diaphragm pump, and a dedicated small-form PC running the Windows XP operating system (Fig. 7). The PSK continuously draws near-surface water by way of a ram intake and pump, routes it through a manifold, and then to flow chambers attached to the YSI 6600v2 and Turner Designs C3. The YSI sonde measures temperature, specific conductivity (salinity), pH, turbidity, dissolved oxygen, and chlorophyll. The Turner Designs fluorometer measures chromophoric dissolved organic matter (CDOM), crude oil, and refined fuels relative to a calibration standard or deionized water. The Sailor Mini-C contains a 12-channel GPS receiver, and Inmarsat-C antenna and transceiver, which provide vessel positioning and data telemetry to the SeaKeepers online data repository. The PSK currently reports samples at 0.0833 Hz, but this value can be increased or decreased by the user. In the coming months, an R.M. Young meteorological station is being added to the Jag Ski and integrated with the PSK system. The meteorological station will provide continuous underway measurements of wind speed and direction, air temperature, relative humidity, and barometric pressure.

If the suite of sensors and measurement capabilities of the PSK are not impressive enough, then perhaps the ability to collect this data while cruising at 40 knots is! The custom-designed ram intake and diaphragm pump allow for a continuous stream of water to be drawn from the near surface (about 10 cm below the surface) regardless of the speed, and the center-point allows it to track with the vessel when turning at high speed (Fig. 8).

The YSI PSK system is playing an important role in the yearlong BP-funded Gulf Research Initiative program that seeks to evaluate the impacts of the *Deepwater Horizon* events on Alabama's coastal resources. With the YSI PSK system, the first synoptic survey of Mobile Bay's near-surface characteristics will be achieved in the summer of 2011. The ability to map a majority of the bay's surface in less than a quarter tidal cycle provides tremendous opportunities for practical, applied research ranging from coastal and estuarine hydrodynamics to watershed management. In terms of the Gulf Research Initiative, the PSK data will be used in combination with the M9 ADCP data to describe transport pathways that are effective in communicating constituent material from the Alabama shelf, through Mobile Bay, and to the Mobile-Tensaw river delta. A number of field experiments are planned for late summer and early fall of 2011 that will isolate the seasonal (i.e. wet/dry, warm/cool, windy/calm) and tidal (i.e. spring/neap) variability of Mobile Bay's dynamics. Beyond academic research, the ability of the PSK to rapidly measure large spatial distributions of dissolved oxygen, turbidity, chlorophyll, and CDOM make it suitable for a number of environmental applications, from tracking and mapping harmful algal blooms (HAB's) to the measurement and analysis of Total Maximum Daily Loads (TMDL) in the Mobile Bay watershed.

While the YSI PSK 1500 has impressive capabilities, its sampling is limited to one location in the water column for the duration of a survey. It is possible to lower the PSK intake to sample from a different portion of the water column, but this is something that would limit the speed of the vessel. Since an estuary like Mobile Bay can be highly stratified at times, the near-surface PSK data may not necessarily be representative of the entire water column; therefore, CTD casts are performed from the PWC at predetermined locations to evaluate stratification at the time of the survey. The idea of performing CTD casts (conductivity-temperature-depth) from a PWC was not practical until the recent release of the YSI CastAway CTD profiler (Fig. 9).

Fig. 7. Internal components of the YSI PSK system. The YSI sonde is on the right, the Turner Designs fluorometer is the black cylinder, the flow manifold is on the left, and the onboard PC is at the bottom. The diaphragm pump is hidden behind the PC.

Fig. 8. The custom-designed center-point swivel and ram intake for the YSI PSK.

Fig. 9. The YSI CastAway CTD profiler and magnetic stylus.

The CastAway CTD has an internal GPS that logs the time and location of each cast. The user-interface is simple and intuitive, and every operation is controlled using a magnetic stylus. Data offloads are accomplished through a Bluetooth connection between the device and a PC running the CastAway software. The CastAway is ultra-portable, making it suitable for deployment from the Jag Ski.

3.1 Case study – Mobile Bay field experiment

A small field experiment conducted on April 1, 2011 in Mobile Bay (Fig. 10) demonstrates the full capabilities of the Jag Ski described previously. The objective of the experiment was to perform a complete hydrographic survey of the lower portion of Mobile Bay during neap tide conditions. An ADCP transect was collected at each of Mobile Bay's primary connections to surrounding water bodies, continuous underway sampling of near-surface waters was performed, and two CTD casts were obtained.

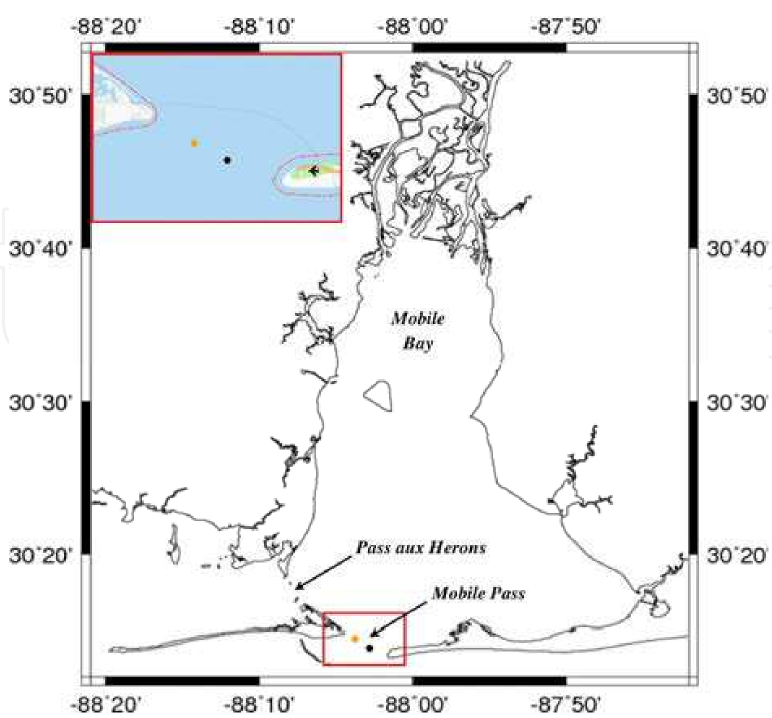

Fig. 10. Overview of study area and locations of CTD profiles at Mobile Pass on April 1, 2011.

The survey took place from 0800 – 1200 hours EDT on Friday, April 1, 2011, beginning and ending at Dauphin Island, Alabama. The tides during the field experiment were in neap, with little variation. Although the survey took place on a falling portion of the tide, the tide was flooding at Mobile Pass and Pass aux Herons throughout the survey, suggesting that the tide propagates into Mobile Bay as a standing wave. A notable departure from the oscillatory tidal signal was evident three days prior to the survey.

Measurements of wind speed and direction, taken from NOAA CO-OPS station number 8735180, for a period four days prior to and during the experiment were analyzed to determine the effects of meteorological forcing on estuarine flows. Conditions during the survey were generally calm, with wind speeds of 3 – 6 m/s out of the west and northwest. Wind speeds were considerably higher three days prior to the survey, and out of the east and southeast. The combination of higher winds and an easterly direction may explain the non-tidal behavior mentioned previously, where Ekman convergence may have produced setup along the Alabama coast. The wind forcing during the study period, however, was weak.

Preliminary (raw) ADCP data at Mobile Pass is shown in Fig. 11. The top panel of Fig. 11 shows the bathymetry between Dauphin Island and Fort Morgan. The middle panel is an overview of the survey location and track, where the green areas denote land. The lower panel of Fig. 11 shows the distribution of velocity magnitude (m/s) across Mobile Pass, where cooler colors denote slow-moving water, and warm colors denote faster-moving water (about 1 m/s). Note that the highest magnitudes occur in the deeper portion of the channel. The total discharge across the pass is nearly 10,400 m^3/s.

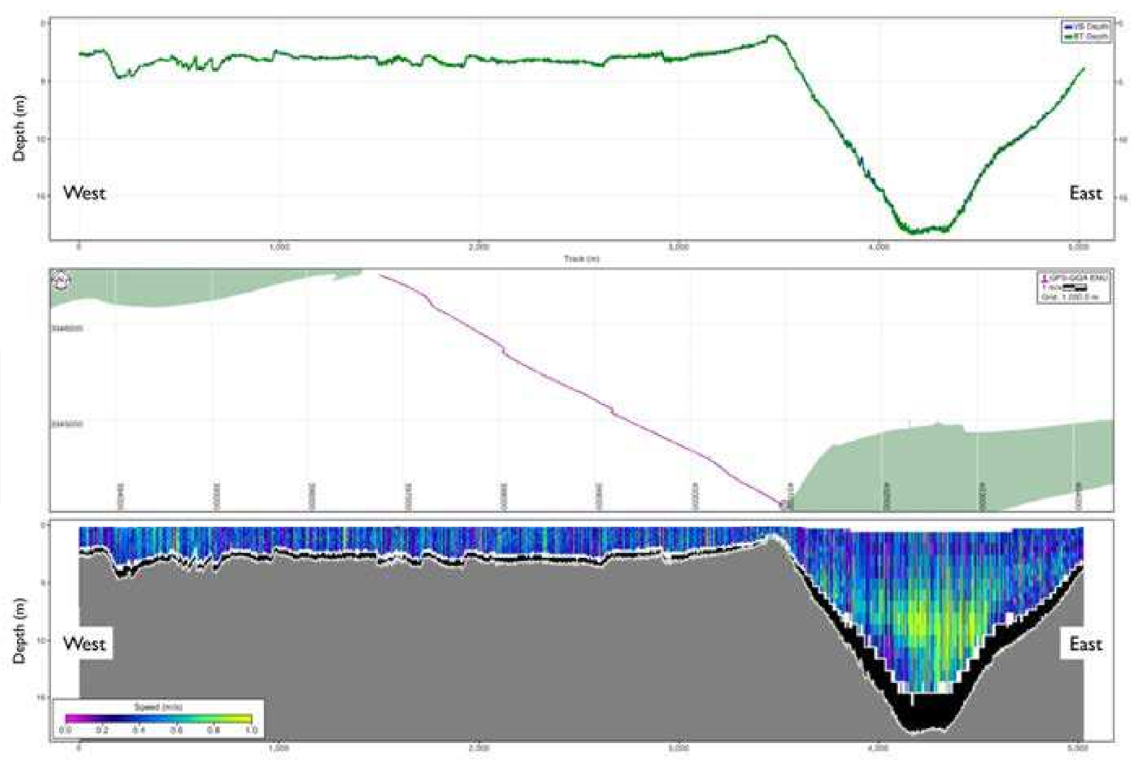

Fig. 11. Bathymetry and velocity magnitude at Mobile Pass for April 1, 2011 during the period 0800 – 0900 hours EDT. The estimated total discharge across the transect was 10,400 m^3/s.

Measurements of flow and bathymetry were also collected at Pass aux Herons, to the west of the Dauphin Island Bridge. The preliminary (raw) ADCP data for Pass aux Herons is provided in Fig. 12. The orientation of the plots in Fig. 12 is slightly different than Fig. 11, where north is on the right side of the page in the upper and lower panels. Similar to the flooding tide at Mobile Pass, the strongest flows are confined to the navigation channel and Grant's Pass (just north of the channel), and attain a magnitude of about 1.2 m/s. Unlike Mobile Pass, however, very strong flows are distributed equally over the water column in the channel and pass. The estimated discharge across this transect was 3,300 m^3/s, or about 25% of the total volume flooding into Mobile Bay during the period 0800 – 1100 hours EDT, April 1, 2011, when considering the discharge across Mobile Pass.

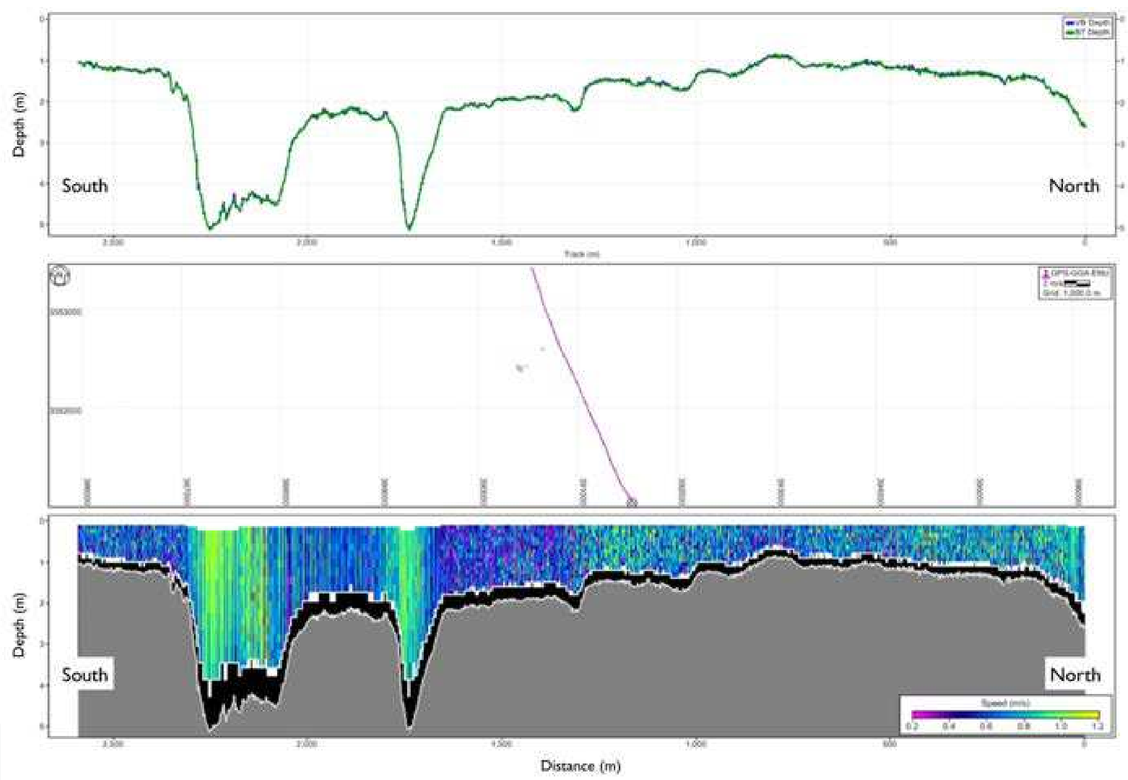

Fig. 12. Bathymetry and velocity magnitude at Pass aux Herons on April 1, 2011 from 1015 – 1100 hours EDT. The estimated total discharge across the transect was 3,300 m^3/s.

An overview of the study area and survey-level view of the CTD locations is shown in Fig. 10. The orange and black dots denote the western and eastern locations of CTD profiles, respectively, provided in Fig. 13. These colors correspond to the orange and black lines in Fig. 13. The vertical profiles of temperature, salinity, and density show only a slight variation over depth near the navigation channel. The CTD cast closest to Dauphin Island suggests a more stratified condition in this portion of the pass, with a notable halocline and pycnocline about 1 to 1.5 m above the bed. Note, however, the very low values of salinity and density at each CTD cast location, even during the flood tide, suggesting the presence of a strong freshwater front.

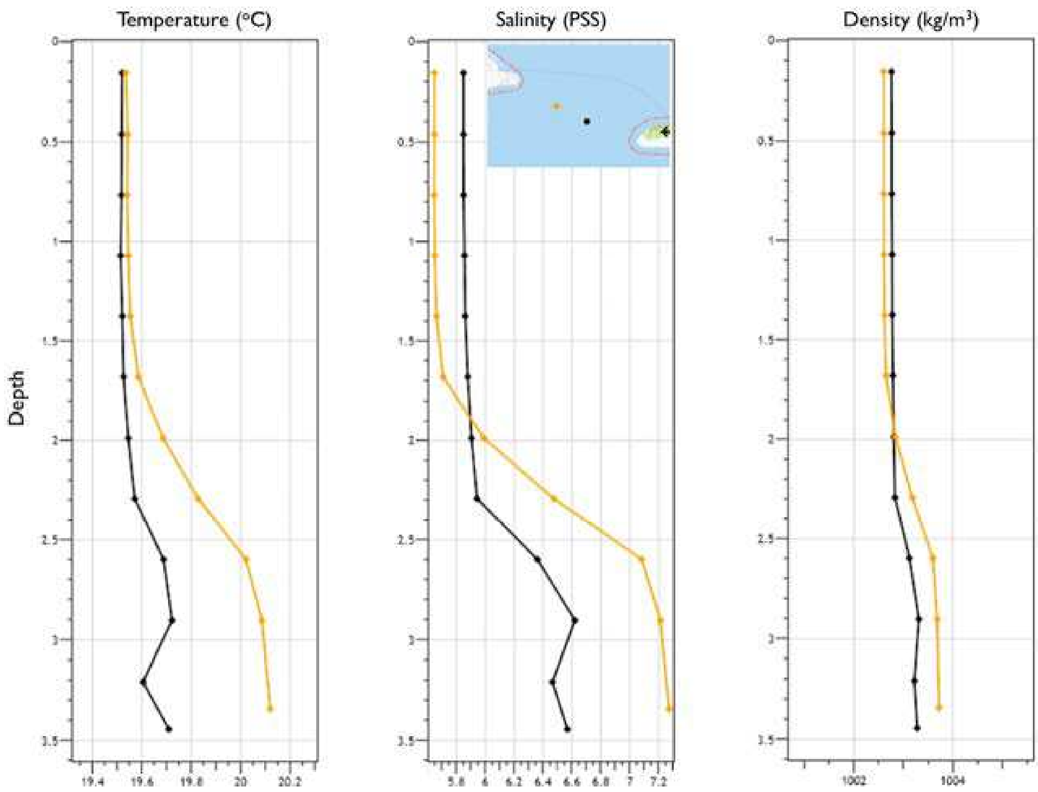

Fig. 13. Vertical profiles of temperature, salinity, and density for two locations at Mobile Pass on April 1, 2011. The orange line represents the western-most CTD cast, while the black line denotes the CTD cast closer to the navigation channel.

Near-surface water characteristics are shown in Fig. 14, where the vessel track is coincident with the spatial distribution of data points. Note the agreement of near-surface temperature and salinity in Fig. 14 with the corresponding values from the CTD profiles shown in Fig. 13. The low salinity environment detected by the CTD profiling is widespread, even on the flooding tide, extending across Mobile Pass and northward into the bay. Values of temperature and salinity entering Mobile Bay from Mississippi Sound across Pass aux Herons, however, were higher. The spatial distributions of near-surface pH, chlorophyll, turbidity, dissolved oxygen, refined fuels, crude oil, and chromophoric dissolved organic matter (CDOM) are also shown in Fig. 14, and their magnitudes and units are specified in each panel. In general, the pH ranged from 7 to 8, the concentration of chlorophyll was low, the turbidity was low, and the dissolved oxygen content was high.

Measurements of refined fuel, crude oil, and CDOM shown in Fig. 14 are made in relative fluorescent units (RFU). For reference, deionized water would have an RFU value of zero, and is commonly used as a calibration standard when the measurement of specific volatile organic compounds cannot be anticipated *a priori*. More simply put, the use of the RFU scale yields a broad-spectrum measurement of the presence of organic compounds in general. In order to measure the volumetric concentration of fuel or crude oil, a corresponding standard would have to be used in the calibration of the instrument. What can be inferred from Fig. 14, though, is that there was a strong return in the measurements of crude oil and CDOM across Mobile Pass and northward into the bay, with much lower values at Pass aux Herons. By comparison, the presence of refined fuels was much weaker, with the exception of one location north of Little Dauphine Island along the centerline of the navigation channel.

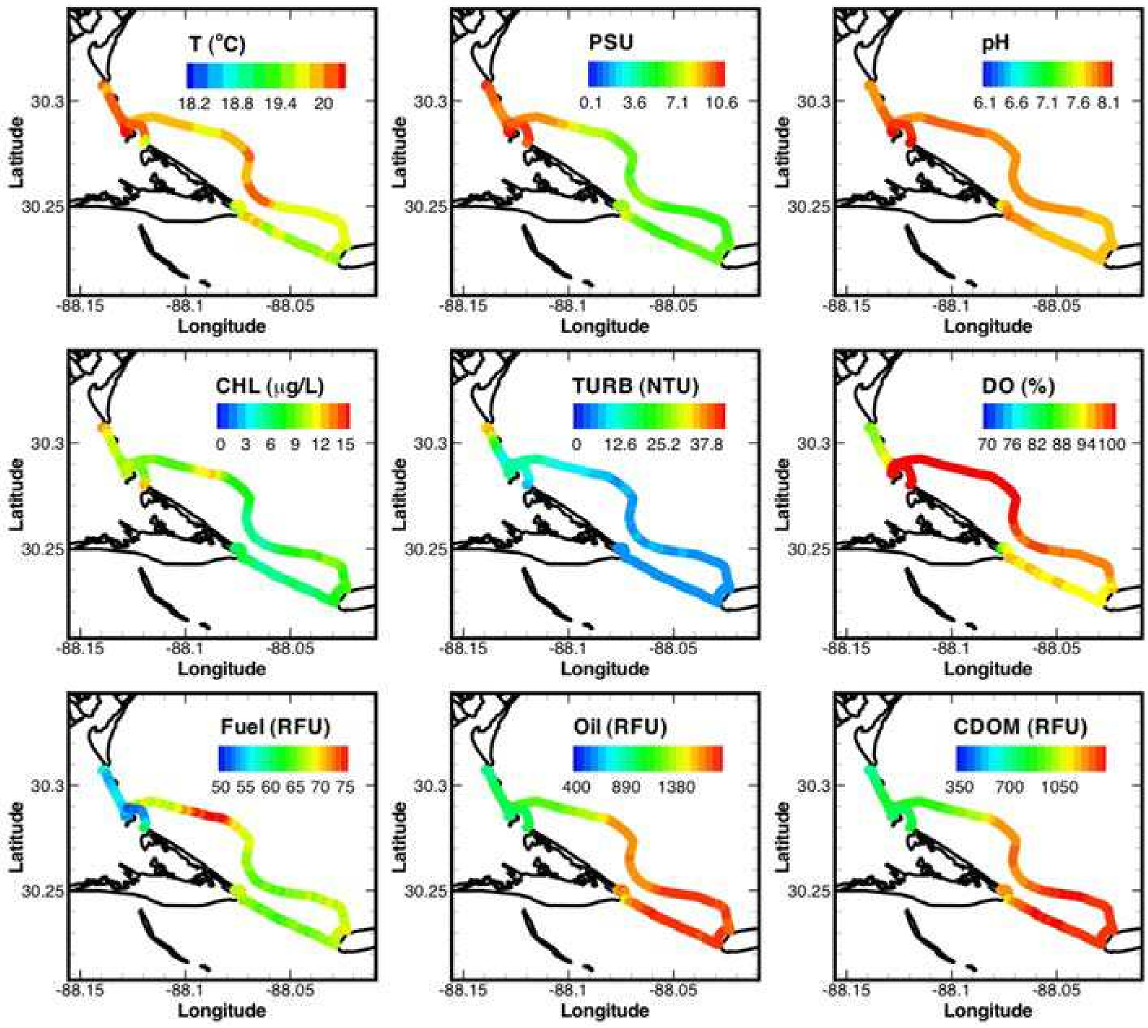

Fig. 14. Near-surface temperature, salinity, pH, chlorophyll, turbidity, dissolved oxygen, refined fuels, crude oil, and chromophoric dissolved organic matter on April 1, 2011. The black line represents the shorelines of south Mobile County, Dauphin Island, and Fort Morgan peninsula. The spatial location of the data points shows the vessel track during the survey.

With each successive deployment, the Jag Ski is demonstrating its utility and reliability as a suitable data collection platform in Mobile Bay's shallow waters. Many have asked why a PWC was chosen instead of a small boat, which might provide more protection while on the water. The simple answer is that in terms of access and ease of use, the PWC cannot be rivaled. The PWC is easy to launch and retrieve, it can be towed by just about any vehicle, and it is much more agile traversing the surfzone than any other craft on the water. In terms of weather conditions, the limitations of the ADCP tend to be more restrictive than the capabilities of the PWC. It is difficult to obtain quality ADCP measurements when the waves are 1 m or greater, but one can still safely operate the PWC in those conditions. Finally, the cost of the PWC is much less than a vessel of any significant size.

4. ***In-situ*** **monitoring: PILS**

An effective complement to a mobile platform is a system of low-cost fixed sensors. The goal of the Pressure-Induced Water-Level Sensor (PILS) is to monitor water level over a long

period of time, so that it can be correlated to wind, tides, and freshwater flow. In order to be able to deploy a large number of sensors, the PILS unit needs to be low-cost. The units are submerged and estimate water level by measuring water pressure. However, water density varies with temperature and salinity, and so, to measure water depth, temperature and salinity also need to be measured. (The salinity cannot be assumed since, in the brackish estuarine environment, it varies widely.)
Measurement of temperature is straightforward, as integrated temperature sensors are readily commercially available. Since the unit will make intermittent measurements with very low power dissipation, the temperature of the interior of the sensor will be extremely close to that of ambient, and so the temperature sensor will indicate the temperature of the surrounding water. A Maxim DS1621 temperature sensor was chosen; it uses the microprocessor's I^2C bus to communicate.
Measurement of pressure is more complicated because the sensor must be able to register changes in pressure. Thus the pressure sensor must lie outside the waterproof housing. A housing for a commercially available low-cost pressure sensor has been developed and tested, and is described in detail below in section 5.
Measurement of salinity is considerably more complicated because of the ionic nature of seawater. The development of a low-cost pressure sensor is detailed below in section 6.
To make measurements over an extended period of time, the system was designed with flash memory to record readings, a real-time clock to simplify the control of periodic measurements, and a low-cost microcontroller. An Atmel ATMega168 microcontroller was selected along with a serial flash memory and a Maxim DS1337 real-time clock chip. A block diagram of the PILS system is shown below in Fig. 15.

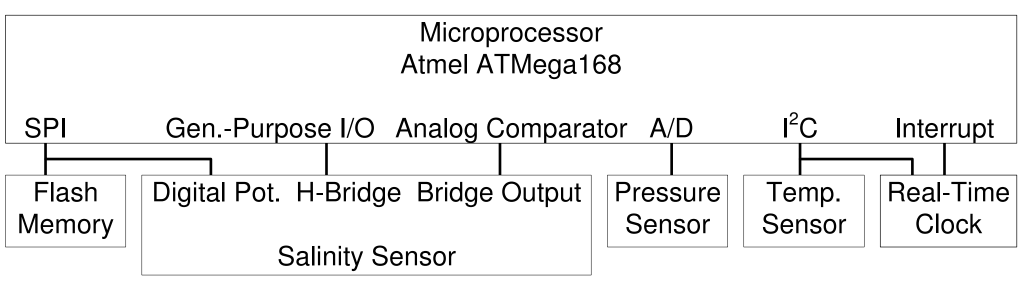

Fig. 15. Block diagram of PILS unit, including its sensor package.

Not counting resistors, capacitors, or a circuit board, the devices listed above have a total cost below $30.
The flash memory is a Winbond W25X80 serial flash. It operates on the microcontroller's SPI bus and has 8 Megabits (1 Megabyte) capacity.
In the process of programming the driver for the flash chip, special considerations were needed to account for the hardware limitations. The problems revolve around the 256 byte page buffer used for programming the flash. If a segment of data was larger than 256 bytes it needed to be broken down into smaller segments. Another, more complicated problem is that the buffer corresponds to a 256-byte page of actual flash (Winbond, 2007). Therefore, if it is necessary to start a segment of data in the middle of a 256 page, it is necessary to end the segment at the end of that page, program the page, and then finish the segment on the next page. These issues were addressed in the design of the flash drivers, and storage of data structures to flash has been tested.
A data structure is needed to store the measurements in flash in an ordered fashion so that they may be retrieved later on. The system must store the time, temperature, pressure, and

salinity. The time requires 7 bytes of space for a detailed time stamp. The temperature needs 2 bytes. Sixty pressure measurements are needed (to provide a sample of wave action). With each pressure measurement using 2 bytes, 120 bytes are needed for the wave and water level data. Finally, 2 bytes are needed for the salinity measurements.
A linked list was selected for storage of the data in the flash memory. Each data structure has a 3 byte pointer at the end which gives the address of the next data structure. This allows the software to traverse the list when outputting the data with ease. Additionally, the microprocessor keeps track of where the next set of data must be placed or the tail of the linked list. This allows for quick storing speed without having to read from the flash. A more complicated data structure is not needed because the only time the data is accessed is when the list is parsed at microprocessor start-up. Thus direct access to the data in the middle of the flash is not needed, only the starting address for output of data and the address of the next available slot for storage of new data.
The clock chip was selected to simplify the process of taking periodic measurements and "sleeping" between measurements. The chip uses a 32.768 kHz "tuning fork" crystal, similar to those in wristwatches, to keep time, and has programmable alarms. When the alarm time is reached, the chip asserts an interrupt that "wakes up" the microcontroller. Thus the entire measurement sequence is inside an interrupt service routine.

5. Low-cost pressure sensor

Since the goal of the PILS project is the development of a low-cost deployable sensor, the design proceeded with a low-cost MEMS-based pressure sensor. A Freescale MPXM2010GS sensor was selected. It measures gauge pressure and has a dynamic range of 10,000 kPa (roughly 1 m of water depth). The limited dynamic range was selected for initial tests due to earlier difficulties with sensors having higher dynamic range.
To amplify the signal coming out of the pressure sensor, an op-amp circuit was designed based on an application note from Freescale (Clifford, 2006). Interestingly, the application note explained how to sense water depth in a washing machine. The output of the op-amp circuit was routed into the A/D converter of an Atmel ATMega 168 microcontroller and software was written to obtain samples periodically from the sensor.
The sensor was connected to a piece of tubing with a balloon on the end, so that the prototype unit did not need to be submerged. The balloon was submerged in the wave tank facility at the University of South Alabama, and six seconds of data were obtained. Pictures of the unit under test and of the data are shown below in Figs. 16 and 17.

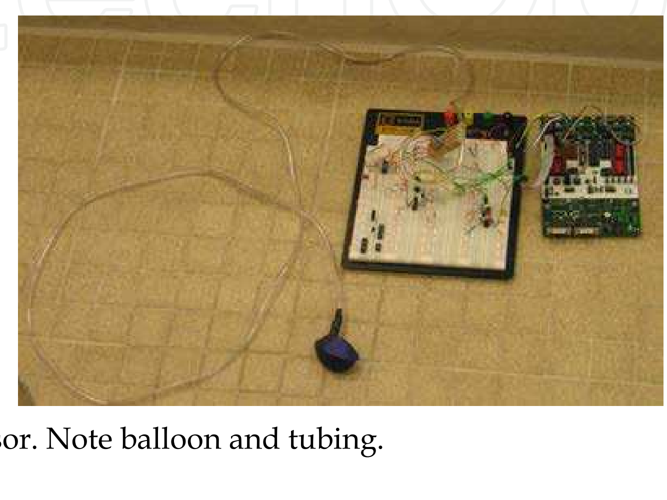

Fig. 16. Pressure sensor. Note balloon and tubing.

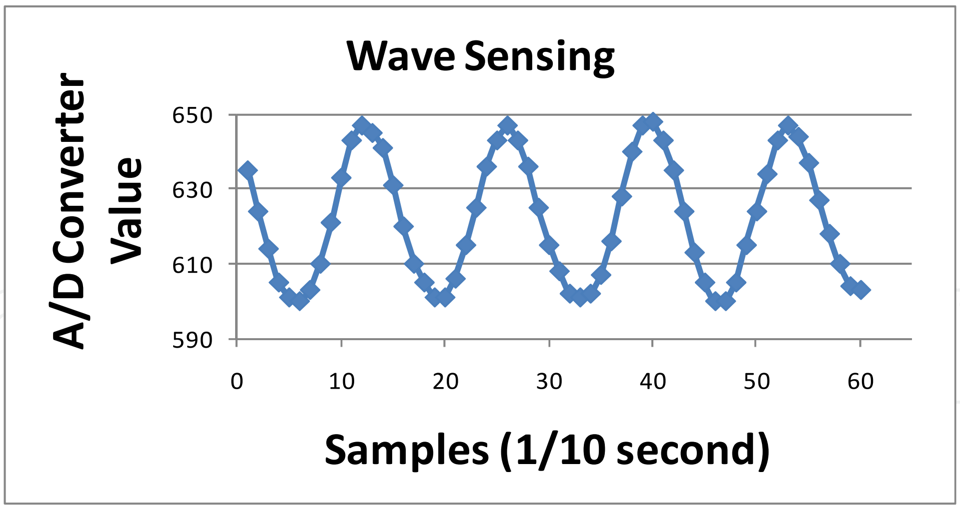

Fig. 17. A/D converter data from the ATMega168. The sample period was 100 ms.

The pressure-sensor data not only measures pressure but also is accurate enough (at the relatively shallow depth of the test) to indicate wave action. Thus the PILS unit will measure not only water level but also wave height.

6. Novel salinity sensor

As noted above, the ability to measure salinity is necessary in order to measure water density and thereby convert a pressure reading to a measurement of water depth. Water salinity can be estimated by measuring the conductivity of a cell of known geometry (that is, the conductance measured between a pair of calibrated electrodes) and then compensating for temperature.

To measure the bulk conductivity of a sample, a set of electrodes of known geometry is used. The set is calibrated ahead of time using solutions of known salinity. The process can be described mathematically as follows.

First, it is well-known that the resistance, R, of a substance can be found as follows

$$R=\rho l/A \tag{1}$$

where ρ is the bulk resistivity of the material, l is the length of the material (in this case, the spacing between the electrodes and therefore the length of the water being measured), and A is the area of the material (in this case, similarly, the area of the electrodes). l/A, then, is the cell constant C which has units of reciprocal-length. ρ is an intrinsic property of the material being measured and C is an intrinsic property of the set of electrodes. (Note that, in this article, we use the terms *resistance* and *conductance* to refer to a measured property of the material being tested and the terms *resistivity* and *conductivity* to refer to the intrinsic property of the material being tested. The actual process will measure resistance and use it to infer conductivity.)

Second, the conductance of a fluid, G, is the reciprocal of resistance (R) and the conductivity of the fluid, σ, is the reciprocal of resistivity R, and so

$$\sigma/G=C \tag{2}$$

Equation (2) can be used to determine the cell constant C by measuring the conductance of a fluid of known conductivity, and can, after being rearranged, be used to determine the conductivity of a fluid by using electrodes of known cell constant C and by measuring conductance.

Third, there are standard equations that are commonly used to estimate the salinity and density of seawater by using conductivity and temperature (Greenberg et al., 1992). Thus the resistance of a seawater sample is measured and converted to conductance, and, using the cell constant C, the conductivity is estimated. The standard equations are then used to estimate seawater density.

Design of a low-cost salinity sensor began with a simple Wheatstone bridge. Its selection was obvious – it permits extremely accurate resistance measurements from imprecise components. For the variable-resistor leg of the bridge, a computer-controlled "digital potentiometer" was used. (An Analog Devices AD8402 was selected.) The selected potentiometer has an eight-bit register that controls the "wiper setting" and so a register value of 0 is minimum resistance and a value of 255 is maximum resistance. A 10kΩ value was selected. (Note that a 100kΩ resistor could be added in parallel for a more accurate reading if so desired.) For the resistor in series with the digital potentiometer, a 20kΩ resistor was selected. For the opposite side of the bridge, the cell (the electrodes to be immersed in seawater) was placed in series with a resistor. The value of the "upper right" resistor is chosen to make the bridge balance across a desired range of salinity, taking into account the geometry of the cell. (The selection process is described in more detail below.) A diagram of the Wheatstone bridge is shown below in Fig. 18.

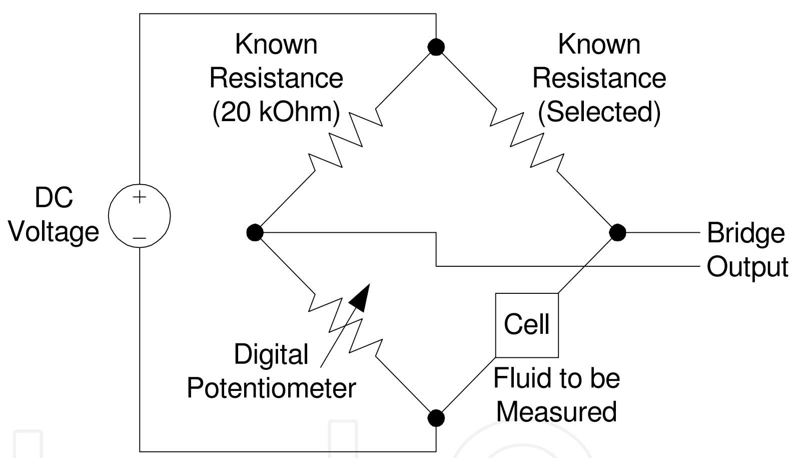

Fig. 18. Wheatstone Bridge used to measure seawater conductance.

The bridge permits an accurate resistance measurement to be made without a precision DC reference, without a current-measuring capability needed, with making only a single measurement (the resistance setting of the potentiometer), and with low-cost components. The measurement process starts by setting the potentiometer to a minimum resistance setting and then increasing its resistance until the polarity of the bridge output reverses. Other algorithms may arrive at a measurement faster, but this algorithm was selected for its simplicity.

To measure salinity, the bridge is first used to measure resistance. Conductance is simply the reciprocal of resistance. From a known, calibrated quantity called "cell constant", the conversion from conductance to conductivity is possible, described in more detail below. The result is a measurement of the bulk conductivity of the seawater.

Initial testing of the Wheatstone bridge was altogether unsuccessful; it never registered a stable resistance measurement.Measurements made with an ohmmeter yielded the same

result. After consultation with a chemical engineering faculty member, it was pointed out that the ionic nature of seawater made a DC measurement impossible. The DC voltages disrupt the ionic distribution of the seawater and resistance measurement is perturbed.
The next step was to replace the DC voltage indicated above in Fig. 18 with an H-bridge. An H-bridge permits the application of a DC voltage in both positive and negative polarity, and is commonly used to control DC electric motors. A Texas Instruments L293D bipolar H-bridge was selected.
During the measurement process, the H-bridge polarity is periodically reversed. More specifically, every time the wiper setting is incremented by one, the polarity is reversed. The software then takes into account that the sign of the bridge output also reverses when the polarity is reversed.
The final circuit is shown below in Fig. 19. Note that the microprocessor's built-in analog comparator was used to lower the cost of the design.
The sensor has an intrinsic limit at the maximum resistance of the potentiometer. Taking into account that fresh water has low conductivity and that conductivity is the reciprocal of resistivity, the result is that the sensor has an intrinsic minimum salinity. The "upper right" resistance in Fig. 19 is selected so that the bridge balances at a high potentiometer setting at the minimum desired salinity reading.
The following process was used to test the circuit over a wide range of salinity.
First, the "upper right" resistance was set so that the sensor produced a reading of decimal 71 (hex 47) at a salinity of 10 parts per thousand (ppt). The resistance value was 38.2 Ohms (56 Ohms in parallel with 120 Ohms).
Second, the salinity was increased in 5 ppt increments, and a resistance measurement made, until a salinity of 40 ppt was reached. (Seawater typically has a salinity of 38 ppt.) The results are tabulated below in Table 1.

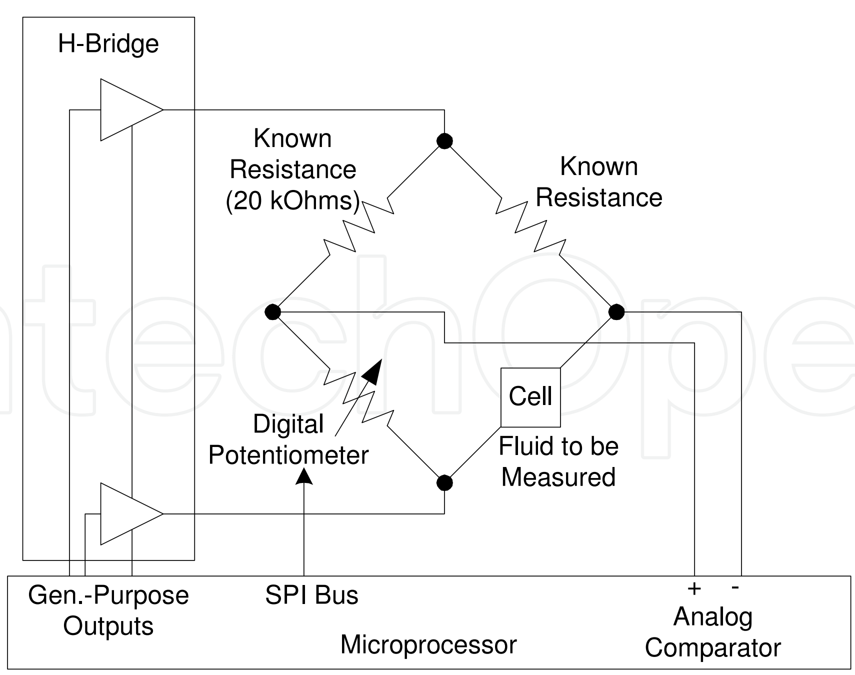

Fig. 19. Final salinity circuit.

The wiper setting is the resistance measurement, where 0 is 0 Ohms and 255 is 10k Ohms. The measured cell resistance is the measured resistance of the cell calculated from the other three bridge resistances. The measured conductance is the reciprocal of the resistance. Finally, the bulk conductivity of water at different salinities is noted from (Weyl, 1964). This last column, then, is the "known" conductivity.

Salt content (ppt)	Digital Pot Wiper Setting	Digital Pot Resistance (Ohms)	Measured Cell Resistance (Ohms)	Measured Cell Conductance (mS)	Bulk Conductivity at 20° C (mS/cm)
10	71	2784	5.32	188.0	15.6
15	51	2000	3.82	261.8	22.4
20	39	1529	2.92	342.3	29
25	33	1294	2.47	404.6	35.4
30	28	1098	2.10	476.8	41.7
35	25	980	1.87	534.0	47.9
40	22	863	1.65	606.9	53.9

Table 1. Measurements used to calibrate the salinity sensor. Bulk conductivity from (Weyl, 1964).

Third, the cell constant of the electrodes had to be estimated from the data. As shown in (2), the cell constant can be estimated by dividing the known conductivity by the measured conductance. The average estimated cell constant over all 7 measurements is 0.0867cm^{-1}. The measured conductivity of the water is plotted against the standard model of the conductivity of seawater using a cell constant of 0.0867 below in Fig. 20.

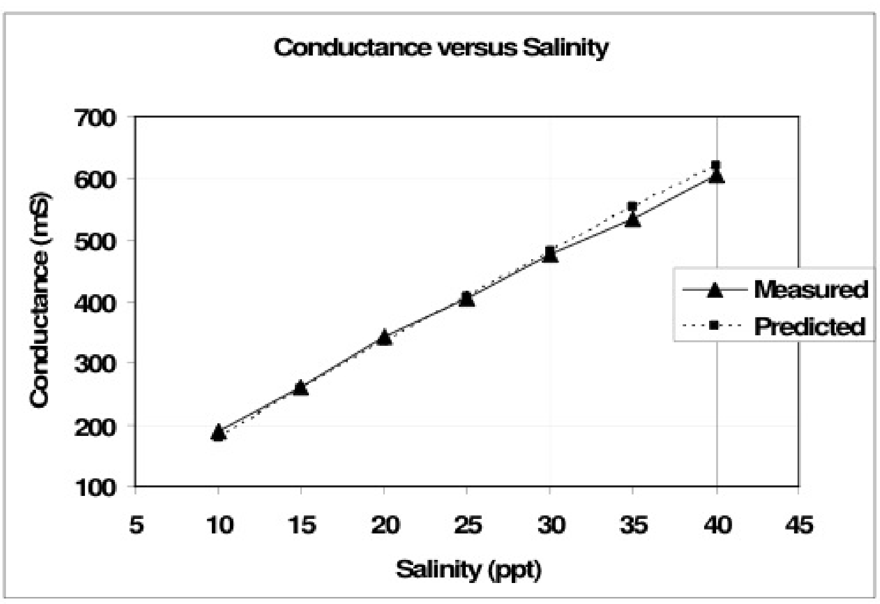

Fig. 20. Correlation of known conductance of seawater (predicted) to actual data (measured).

7. Conclusion

The Jag Ski provides a unique opportunity to collect hydrographic and environmental data in shallow and remote areas typically inaccessible by traditional watercraft. Aside from its

utility as a hydrographic data collection platform, it is small, inexpensive, and relatively easy to maintain. Where a traditional vessel may require two or more people to launch, operate, and recover, the PWC can easily be attended by one person if needed. With the recent addition of the Portable SeaKeeper system, the Jag Ski's capabilities have expanded tremendously. The ability to map large spatial areas in a relatively small amount of time is very helpful in coastal applications, mainly because it reduces the tidal bias of the collected data. The Jag Ski's speed and ease of deployment will also provide opportunities to perform episodic surveys of coastal waters to determine the effects of storms or other events on the near-surface water chemistry of Mobile Bay, Mississippi Sound, and nearby rivers.
The PILS unit combines low-cost components, including a novel low-cost salinity-measuring circuit to provide a powerful and inexpensive environmental-monitoring capability. The sensor package can readily be modified for other, similar missions. For example, development is underway, using the microprocessor, clock, and salinity sensor, to develop a system to control periodic GPS measurements and satellite transmissions to develop a low-cost drifter to measure surface currents in the open ocean.

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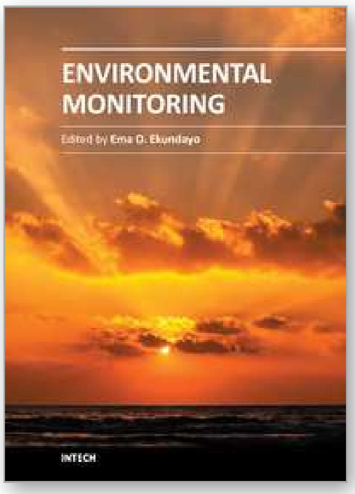

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