

High Fidelity Hydrographic Surveys Using an Autonomous Surface Craft

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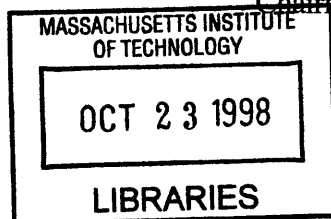
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Abstract

There is a vital need to update the hydrographic database of the United States. NOAA statistics show that with current survey technologies it will take nearly 40 years to update U.S. nautical charts. Hydrographic surveys require a careful record of depth, position, tide, and the motions of the survey platform. The U.S. Army Corps of Engineers is one highly regarded organization which performs hydrographic surveys. They impose a strict standard of accuracy for certain surveys. For these Class 1 surveys, position must be within 6 meters and depth must be measured within 0.5 feet. This thesis documents the development of a new technology to meet these needs and provide hydrographic surveys in more cost effective ways than existing techniques.

Since 1993 Autonomous Surface Craft (ASC) have been under development at the MIT Sea Grant College Program. Hydrographic surveying was the first practical mission approached by an ASC. The ASC ARTEMIS used simple navigation and control systems and a basic recreational depth sounder to demonstrate the possibility of performing surveys with ASC. This background led to the developments presented here.

This project had two goals, the first was to develop an ASC which was better suited for hydrographic surveys than ARTEMIS. This required designing and constructing a new ASC with improved endurance, speed, payload, and stability. This goal was met with the development of the ASC ACES (Autonomous Coastal Exploration System). The development of ACES and its preliminary field tests, which provided a hydrographic survey which was 78% Class 1, are documented in this work.

The second goal of this effort was to configure the new ASC for high fidelity hydrographic surveys. This required selection of new sensors to measure position, depth, tide, and the motions of the ASC. Conventional systems were evaluated and a final design was selected which incorporated the latest developments in the application of the Global Positioning System (GPS). By using GPS sensors to account for all variables except depth, ACES is able to meet the high standards of a Class 1 survey. Using an Acoustic Doppler

Current Profiler to measure depth provides ACES with a high quality and versatile sensor to employ in such surveys.

This project has demonstrated the potential for ASC to be used in the field of hydrographic surveys. ACES, A system capable of providing high fidelity hydrographic surveys to meet the needs of the U.S. survey community has been designed and built. This system has matched the USACE surveys with 78% accuracy in a prototype configuration. The final high fidelity survey configuration of ACES will provide Class 1 or better surveys more cost effectively than manned survey vessels.

Acknowledgements

This work is dedicated to the memory of my Mother. Were she here today, I'm sure she would find some remaining grammatical error and smile. I also must thank my many close friends who supported me through the tumultuous process of completing my Master's degree and plotting my future course. I am forever indebted to you all.

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I) Introduction - The Need for New Survey Assets

Seventy percent of the Earth's surface is covered by water. In order to understand the nature of the surface under the water, humans have spent many centuries exploring the depths of the oceans. First, simple visual inspection through clear waters was the best method available. With time, men ventured further from shore in ships. Dredges brought samples from the bottom of the oceans into the light of day. Gradually, it became desirable to identify the depth of the oceans. This information was of interest to both scientists and to mariners. When the first captain dropped a weighted line to determine the depth of a new harbor, the science of Hydrography was born.

According to the International Hydrographic Organization, Hydrography is defined as "the science of measuring and depicting those parameters necessary to describe the precise nature and configuration of the seabed, its geographical relationship to the landmass, and the characteristics and dynamics of the sea." This science studies many different parameters of the seabed including; "Bathymetry, tides, currents, waves, physical properties of seawater, geology and geophysics" [1]. This work is primarily interested in the first two parameters. The depth of the ocean and the role of tides are important factors to those who make regular use of the oceans.

The oceans play many important roles on the planet, from climate regulation to providing a valuable source of natural resources. One role, with which nearly every individual can relate, is the transportation of people and goods over the seas. A quick glance around almost any home or office reveals some item brought from distant lands at reasonable cost and in good time by a ship. To insure the safe passage of these ships it is necessary to identify what waters are deep enough to be safely navigated by large cargo vessels. This information is provided by hydrographic surveys.

This work will discuss the development of a new tool to carry out these surveys. Some justification for the development of a new method will be

given in this section. It will be followed by background information including an explanation of parameters important to hydrographic surveys. The remainder of this work will explain the details of the development of a new survey tool and how it collects hydrographic data.

1.0 Navigation Charts are Outdated

The need to update the hydrographic databases used in the production of nautical charts is clear. The collection of hydrographic data is the responsibility of the National Ocean Service (NOS) which is a branch of the National Ocean and Atmospheric Agency (NOAA). In one publication the U.S. National Geophysical Data Center states:

The NOS hydrographic Survey database is a historical set of surveys. In fact, some of the digital data sets are digitized from surveys that were conducted in the late 1800's! Accuracy is difficult to determine for these surveys [2].

NOAA is equally frank about the problem and states in the executive summary of its strategic plan that "60% of NOAA's nautical charting data were obtained before 1940" [3].

Some additional statistics provided by NOAA [4] are enlightening.

- 50% of inshore surveys (depths less than 30m) that support U.S. charts are over 50 years old. 25% of harbors and approaches are in this category.
- Over 20,000 reported but unsurveyed wrecks and obstructions. 200 wrecks and obstructions are resolved yearly. 500 new features accumulate yearly.

While these statistics indicate a problem, a more disturbing prospect is NOAA's Critical Survey Area Requirements. Critical Survey areas are regions where "there is inordinate risk that an inadequate chart will contribute to a marine accident resulting in casualties, property damage, or substantial environmental damage." The critical survey needs are itemized in Table 1.1.

Region	Square Nautical Miles to be Surveyed
East Coast & Great Lakes	5,100
Gulf of Mexico	14,700
West Coast and Alaska	23,400
Total	43,200

Table 1.1: Critical Area Requirements [4]

The need for more high accuracy bathymetric data was pointed out in a recent investigation of the risk of ship groundings. This study stated that “there is no question that masters take risks when navigating in and out of ports.” Therefore, “the need for better bathymetry around shipping routes is a prime concern to maintain safe and efficient commercial transportation.” This study also cites a survey of “chart users” conducted by NOAA which “revealed that more detailed and accurate bathymetry was requested by all user communities” [5].

1.1 Current Hydrographic Data is not Sufficiently Accurate

In addition to great portions of the national hydrographic database being out of date, the information collected by prior surveys is no longer accurate enough to support modern navigation. A problem with hydrographic data is that it is not always collected with the same precision now available to mariners in current navigation systems, notably the Global Positioning System (GPS). Some studies suggest that “this may have eroded some of the safety margin that was previously incorporated into the charts” [5]. NOAA is even more critical and states that while “mariners can now position themselves to within 3-5m, practically all prior surveys have larger positional errors (15-50m)” [4].

While the position information of current data may be poor, its coverage of the sea floor is also inadequate. Early survey methods used lead-lines or single beam depth sounders to take spot soundings along a designated sur-

vey track. Typically, soundings were collected every 10 to 30 meters along parallel paths 50 to 300 meters apart. This type of survey produces a data set like that shown in Figure 1.1. This sparse data is then interpolated to produce a contoured depth profile on a nautical chart. If a region has particularly rough terrain consisting of rock formations like the one shown in Figure 1.2 they could go uncharted by a typical survey.

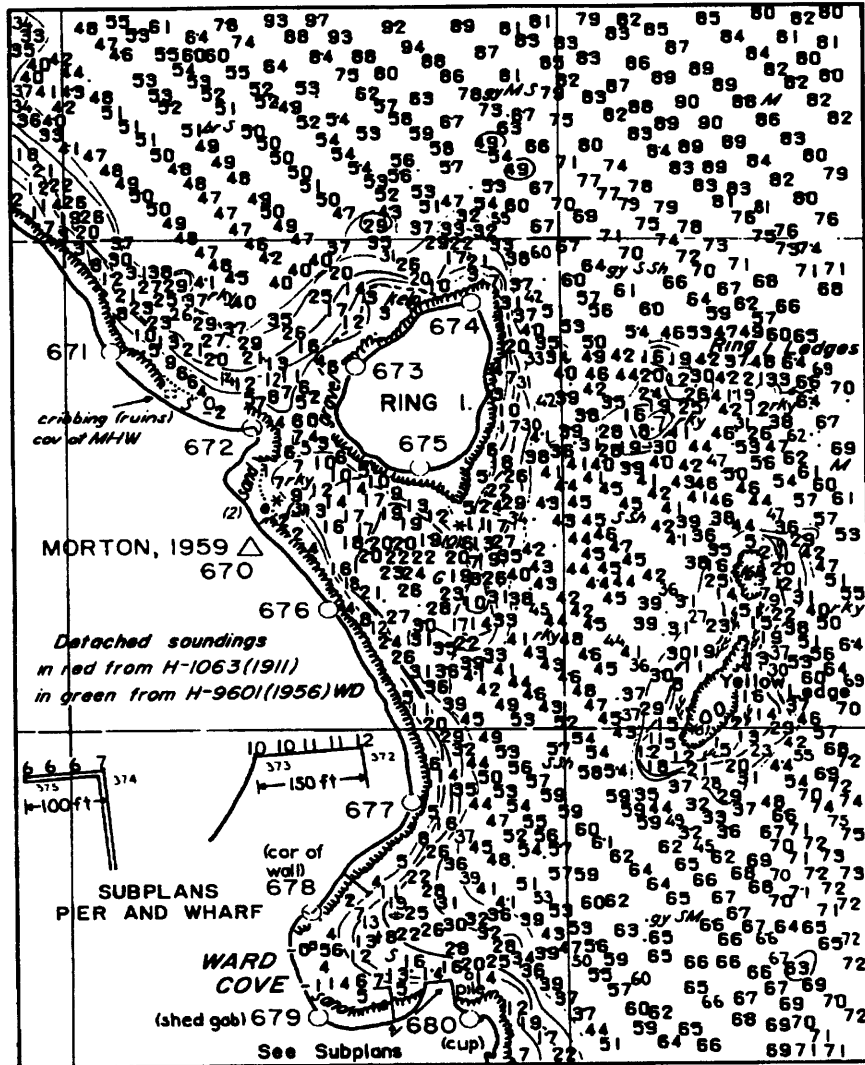


Figure 1.1: A Hydrographic Data Sheet which is Interpolated into Charts [4]

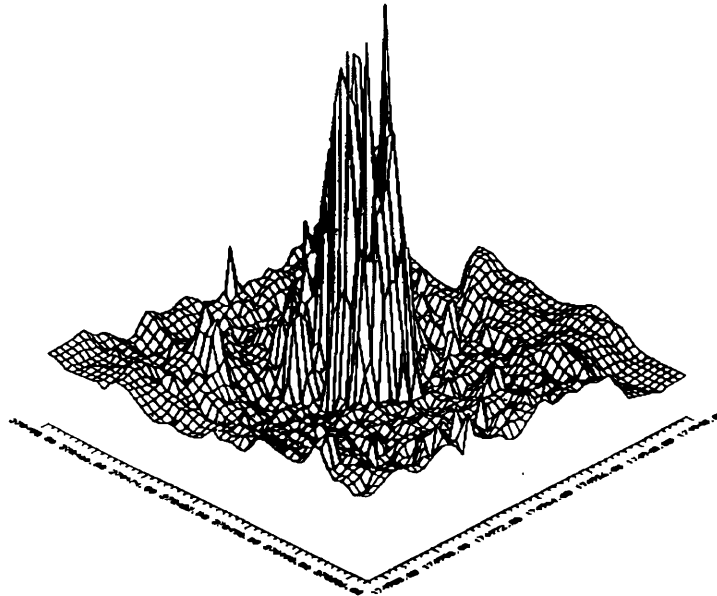


Figure 1.2: An Outcropping which Conventional Surveys could Overlook [4]

This type of error has caused accidents in the past. In New York Harbor, a recently dredged channel was surveyed by both the dredging contractor and the U.S. Army Corps of Engineers and certified as clear. The first ship to transit the channel struck an obstruction. This proved to be a set of pilings which both surveys had missed because they could not focus their searches tightly enough to pick up a small (yet dangerous) obstruction [6]. An overlooked shoal was also the cause of the highly publicized grounding of the Queen Elizabeth II off Massachusetts[5].

The hydrographic database for the United States is both out of date and potentially full of inaccuracies. One detailed case study of hydrographic survey needs is provided by the Port of Houston, Texas.

1.2 The Port of Houston

The Port of Houston was the second largest port (by tonnage) in the U.S. in 1995. Houston handled a total of 135,231,322 tons in 1995. The nearby port of Galveston handled an additional 10,465,119 tons making it the 53rd largest port in the U.S. [7]. Between 1981 and 1995 there were a total of 602

groundings in or near these ports. This is an average of 43 groundings per year [5]. Unfortunately, the accident records maintained by the U.S. Coast Guard only identify the incidents as groundings. The cause is not identified. However, given the fact that the port of New York, the third largest port by tonnage in 1995 [7], experienced groundings due to poor surveys, it is reasonable to assume that at least a small percentage of the groundings in Houston were due to inaccurate charts. Figure 1.3, below, shows a NOAA map of the Gulf of Mexico. It can be seen that only a small portion of the Gulf (dark shaded region) has been surveyed since 1959 and much of the coast surrounding Houston (yellow region) was last surveyed before 1940. Table 1.1 pointed out that 14,700 square miles of the Gulf Coast, including 522 square miles near Houston/Galveston [4], are identified as Critical Areas for re-surveying by NOAA. The fact that the second largest port in the United States needs 522 square miles of accurate new survey coverage is an excellent example of the urgent need for more high accuracy hydrographic data.

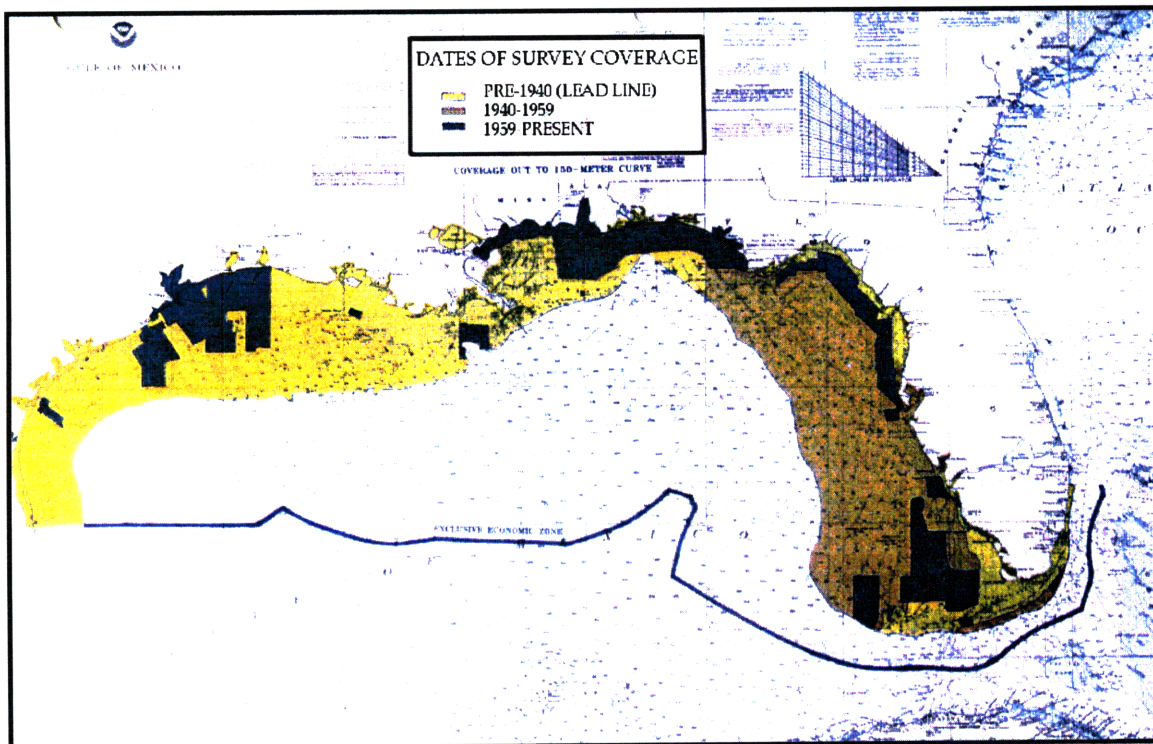


Figure 1.3: Survey Dates along the U.S. Gulf Coast [4]

1.3 The Challenges of Hydrographic Data Collection

While it is apparent that obtaining new hydrographic data is essential to provide accurate nautical charts for the ports and waterways of the U.S., it is not so apparent why this is so difficult. An investigation of current hydrographic data collection resources available to NOAA reveals that current survey assets are declining while survey requirements rise.

Bathymetry for the coastal waters of the U.S. is obtained by NOAA using large survey vessels. Figure 1.4 shows one of these vessels at sea. In 1994 NOAA fielded total charting resources of two 231' vessels (each carrying 4 survey launches), one 163' ship (with 2 survey launches), two 90' ships, and two field parties equipped with a total of 7 small boats. While at first glance this sounds impressive, it actually represents a 60% decline in NOAA's resources since 1977 [4]. Figure 1.5 shows the decrease in Days of Active Surveying represented by NOAA's fleet since 1977.

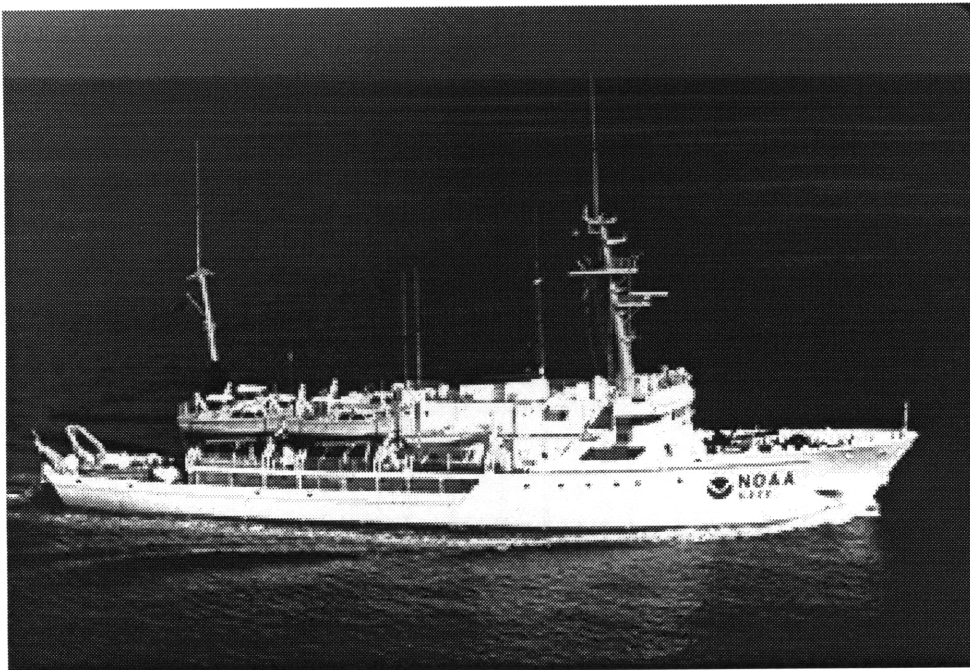


Figure 1.4: A NOAA Hydrographic Survey Vessel [8]

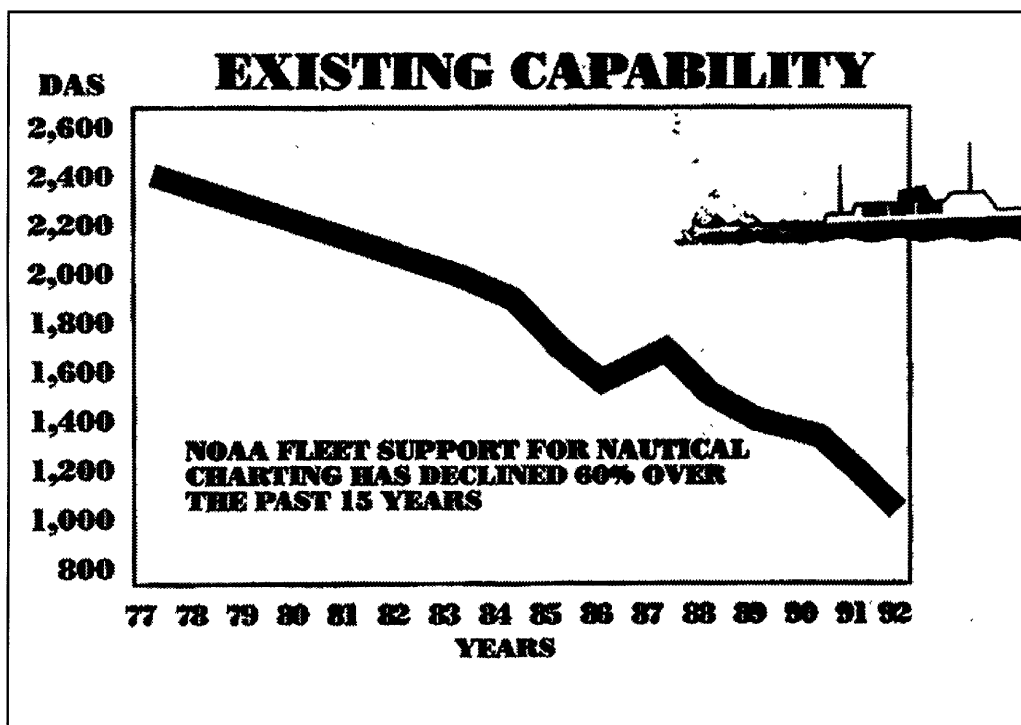


Figure 1.5: NOAA's Declining Days of Active Surveying [4]

The decline in NOAA's survey resources is particularly alarming when compared to the Critical Area survey needs (Table 1.1). The current survey assets used by NOAA allow 1,100 square miles to be accurately surveyed each year. This means that the entire 43,200 square miles of Critical Areas will take 40 years to be properly surveyed with current resources [4]. To resolve survey inaccuracies in the Houston area alone, would take nearly six months if NOAA directed all of its resources there.

The key reason for the decline in hydrographic surveying capabilities is high cost. The U.S. Army Corps of Engineers (USACE) New England District Survey Branch provides a good example of these costs. To meet survey needs in Federal navigation channels and inland waterways between New York and Canada the New England Survey Branch has a budget of \$1.8 million. This budget provides for three survey teams each equipped with a boat which must be driven on trailers to survey sites [6].

While these resources are adequate to provide current service, the need to improve survey coverage and quality has already been identified. To meet this goal, the New England District has recently selected a multibeam sonar system to collect bathymetric data. This represents a significant improvement to survey quality. The rock formation shown in Figure 1.2, which conventional surveys might overlook, was identified with a multibeam sonar system. This new technology is vital to improving survey quality and coverage but it is very expensive. One of these systems costs approximately \$200,000 dollars. To equip all three of the New England District's survey teams with multibeam sonars will cost \$600,000 which is a third of their total budget. In addition to their high cost, multibeam sonars are also difficult to accurately calibrate. The New England District's survey branch has experienced difficulties in obtaining consistent results with their multibeam unit so they are currently relying on older proven technology [6].

The high cost of hydrographic surveys has led to a gradual decline in survey assets. The increased cost of updating the hydrographic database of the United States is a significant challenge to providing adequate nautical charts of U.S. ports and waterways. A way to maximize the potential of current funding is essential if hydrographic survey needs are to be met with high quality data. Multibeam sonars are one answer to increasing data coverage and quality, but due to budget restrictions they will not be able to provide the bulk of bathymetric data for the next ten years and in some cases they are "overkill" for the particular survey needs. Given the financial and technical challenges facing wide usage of multibeam sonar systems, there is interest in developing an interim system which can address both the current data needs of NOAA and the USACE yet still provide a useful hydrographic survey asset after multibeam systems become more prevalent. This work will document the development of such a system.

II) The Science of Hydrographic Surveys

Before further details on the development of a new hydrographic survey tool are presented it is important to define the parameters involved in such surveys and account for the current methods of collecting hydrographic data. The depths of the oceans have been recorded for many years and the science of Hydrography has a long history. Given the expanse of the oceans, it is not surprising to find a variety of organizations interested in collecting hydrographic data. Fortunately, most nations realized that standardizing the collection of hydrographic data and the production of nautical charts was beneficial to all parties. This led to the creation of the International Hydrographic Bureau (IHB) in 1921. The role of this organization is worthy of a brief discussion.

2.1 Hydrographic Survey Standards and Organizations

2.1.1 The International Hydrographic Community

The member states of the IHB adopted the new name International Hydrographic Organization (IHO) in 1970. The name IHB came to refer to that organization's headquarters which was in Monaco. The objectives of the IHO include "the coordination of the activities of national hydrographic offices and adoption of reliable and efficient methods of conducting hydrographic surveys" [9]. These goals are accomplished through the actions of several working groups and committees. The activities of these bodies include development of standards and specifications for hydrographic surveys. These are distributed to Member States for ratification. In addition, the IHB produces many publications, including references, charts, and a technical journal, the *International Hydrographic Review* [9]. These resources are widely used by the international hydrographic community.

The IHO serves as the focal point for a large number of national hydrographic agencies collecting hydrographic data. A list of nations which participated in IHB activities as early as 1967 (before it became the IHO) includes: Brazil, Burma, Canada, Chile, Denmark, France, Germany (then the Federal Republic of Germany), India, Italy, Korea, Netherlands, Portugal, Philippines, Spain, Republic of South Africa, United Kingdom and the United States [10]. The number and diversity of these nations demonstrates widespread and significant interest in hydrographic surveying throughout the world. This level of cooperation has continued, and today IHO requirements are considered the international standard for hydrographic data collection.

2.1.2 Hydrographic Surveying in the United States

While the IHO is responsible for developing internationally recognized survey standards, the United States has its own diverse survey community. The National Ocean and Atmospheric Agency (NOAA), introduced in Chapter I, is responsible for most nautical charting and its requisite hydrographic surveying in the United States. This is especially true in deeper open ocean waters. However, there is a second Federal agency with a vested interest in hydrographic surveys.

The United States Army Corps of Engineers (USACE) “is responsible for the operation and maintenance of the Nation's waterway system to insure efficient and safe passage of commercial and recreational vessels” [11]. This responsibility involves a great deal of hydrographic surveying. For supporting dredging operations, placing of aids to navigation, and many other engineering projects on the Nation's waterways the USACE requires a large amount of hydrographic data.

The recent decline in NOAA survey resources and the growing need for additional hydrographic data has led to the suggestion that NOAA follow the model established by the USACE to help fill the need for additional data. This could encompass direct use of USACE survey teams or subcontracting

through the network of commercial surveyors the USACE has cultivated [12]. This growing future collaboration, along with an overall international respect for USACE survey skills, makes an investigation of their survey techniques valuable background information for this work. The remainder of this chapter provides an explanation of the current methods of hydrographic surveying practiced by the USACE. It is meant to serve as the benchmark by which the new survey system presented in later chapters is measured.

2.1.3 USACE Hydrographic Surveying

The USACE has developed three classes of surveys. These are Class 1 used for contract payment surveys, Class 2 used for project condition surveys, and Class 3 used for reconnaissance surveys. Surveys to Class 1 standards which “require the highest level of accuracy” are “intended to encompass all work associated with contract construction activities of USACE, most particularly those surveys performed to measure the amount of excavated, deposited, and/or placed material in subsurface areas” [13]. The parameters in a Class 1 hydrographic survey will be explained in detail so that the reader may understand the tasks performed during a hydrographic survey.

2.2 USACE Class 1 Hydrographic Surveys - Data Types and Standards

The result of a Class 1 survey by USACE is usually an engineering drawing which shows the body of water in question in relation to the surrounding shore. The two most important parts of the drawing are position and depth. A final drawing must clearly show the position of each measurement and the depth of water at that point. These two parameters must be within a tight tolerance in order to be considered Class 1. The remainder of this section will define the data which is collected in order to produce these drawings and the standards which it must meet.

2.2.1 Position

The first type of data required during a survey is the position of the surveyor. Identifying the location of any object requires a reference point. One common reference system, to which most people can relate, is the latitude longitude system. This system of geodetic (also known as geographic) coordinates provides a system which locates any given point in reference to the surface of the earth. This is the most general type of position which can be identified. A Class 1 survey requires a more local type of position information since it is much more important to know the position of items within the project scope rather than on a global scale.

USACE hydrographic surveys are based on any local reference system which allows for easy measurements. These are then referenced to one of a number of National coordinate systems. The National Geographic Reference System (NGRS) consists of a series of benchmarks which are small monuments stamped with the exact coordinates of that location. Within the United States these coordinates can be measured by a local State Plane Coordinate System (SPCS), the North American Datum of 1927 (NAD 27), or the North American Datum of 1983 (NAD 83). Currently NAD 27 is the most commonly used datum in USACE surveys but NAD 83 is the preferred datum and all surveys are slowly being converted to this standard. Formulas and software routines are used to allow conversion between these various datums [13].

Once a reference datum is selected, the accuracy of the position measurements must be examined. In this case, accuracy is defined as “the closeness of measurements to their true or actual value” [13]. The USACE defines deviation RMS (DRMS) as a measure of position accuracy. One DRMS indicates that, with a probability of 63.21-68.27%, a sample point is within an error circle drawn about the point. The radius of this circle is what is measured by DRMS. So a position measurement made to 1 meter DRMS will be within a 1 meter circle of its true value with a probability of 63.21-68.27% [13].

To identify position in Class 1 surveys the USACE requires 2 DRMS accuracy. This increases the probability that a sample point will be within the given error circle to 95.45-98.17%. 2 DRMS is roughly twice 1 DRMS. Therefore, 3 meters (1 DRMS) is equal to 6 meters (2 DRMS) which is the allowable radius for the error circle in a Class 1 survey. If a Class 1 survey has been performed it is safe to say that with approximately 95-98% certainty the positions measured are within 6 meters of the true location [13].

2.2.2 Depth

The feature of interest in a hydrographic survey is the depth of the water in the survey area. The idea of water depth is relatively straightforward and does not require much more explanation. A variety of methods are used to measure depth. The accuracy of depth measurements, however, is influenced by several parameters which will be described in the following sections. This section will present the definition of the accuracy standard for depth measurements in a USACE Class 1 survey.

A one dimensional measurement, such as depth, can have two types of errors, random errors and biases. Random errors are unpredictable, whereas biases can usually be eliminated by careful calibration of the system and observance of appropriate procedures. Tightly grouped measurements reduce random error and scattered measurements reduce bias errors. A mean square error (MSE) can be defined by the combination of these errors. Figure 2.1, below, shows the relationship between random errors, biases, and measurement grouping, as well as the formula for the MSE.

Based on this definition of MSE, the USACE defines the “one-sigma” error. The magnitude of the random error is referred to as the standard deviation. When normally distributed, as shown in figure 2.1, the one-sigma error includes about 68 percent of the area of the function. A depth measurement made to one-sigma accuracy will have a 68.27% probability of being

the true value. For USACE Class 1 surveys the depth must be measured within one sigma, to an accuracy of 0.5 feet [13].

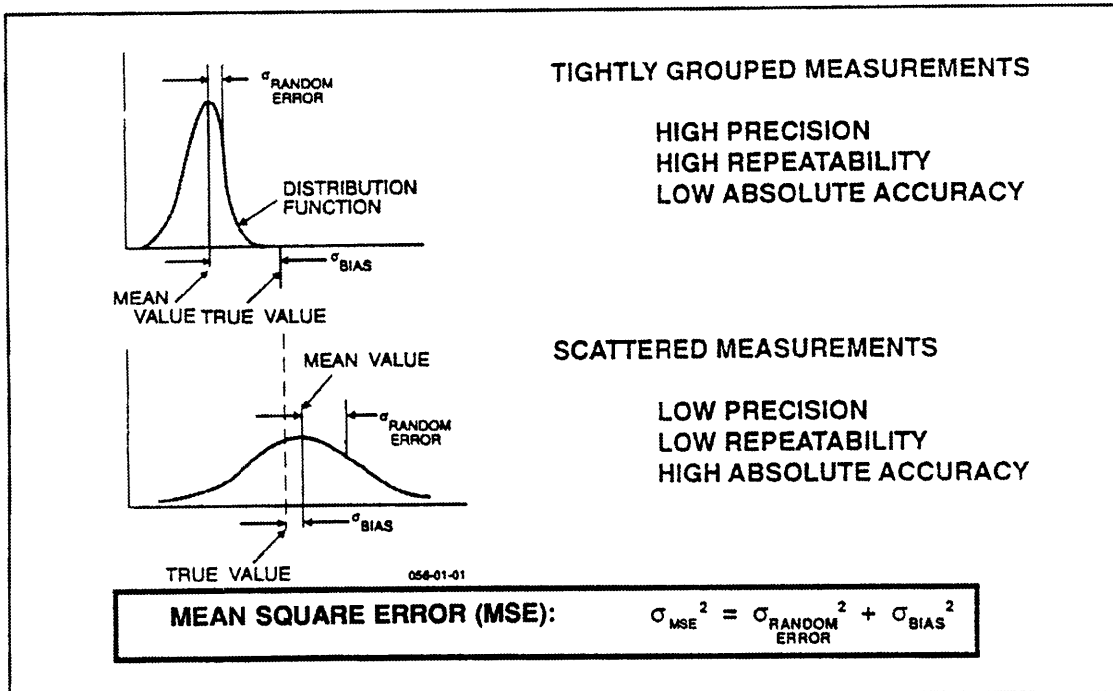


Figure 2.1: Definitions of Depth Measurement Errors [13]

2.2.3 Vessel Motions

One of the key parameters influencing the depth measurement made during a hydrographic survey is the motion of the survey vessel. The dynamic nature of the ocean surface causes survey craft to move in a variety of directions. Figure 2.2, below, shows the six different types of motion a vessel can experience. Three of the six motions, yaw, sway, and surge do not cause errors in depth measurement as they have only horizontal influences on the vessel and its depth sounder. The remaining three motions can cause errors in both the position and the depth measurements. Figures 2.3 and 2.4, below, illustrate the effects of roll and pitch. These figures demonstrate the influence of vessel motions on a survey using electronic positioning systems and an electronic echo sounder. These are the most common types of surveys

equipment currently used so these illustrations are most effective in this form.

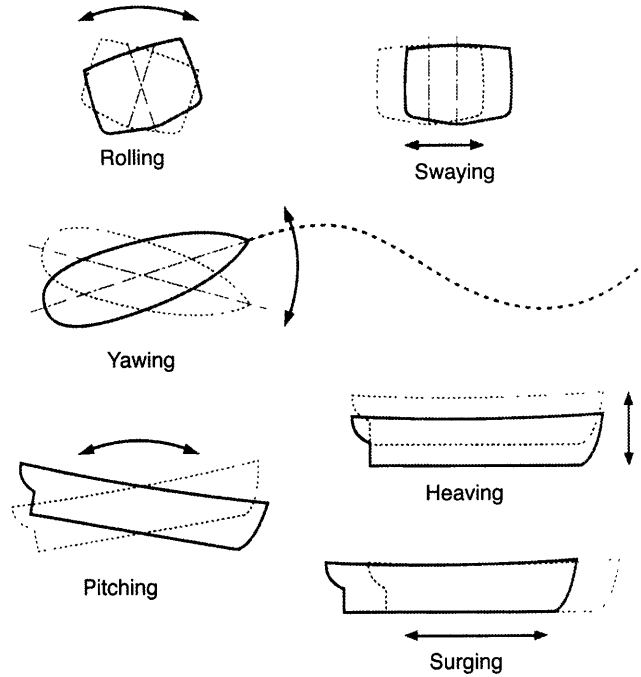


Figure 2.2: Vessel Motions Defined [14]

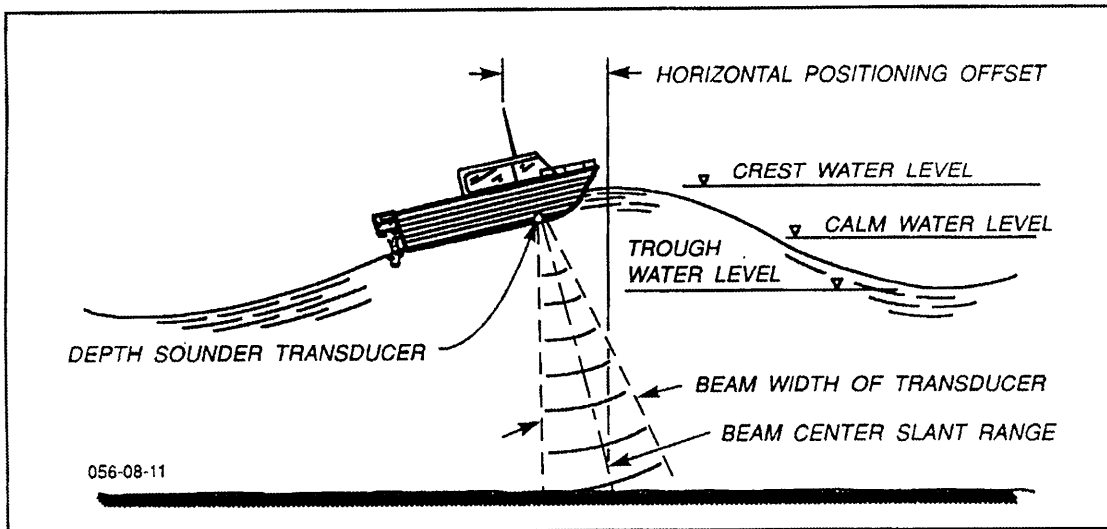


Figure 2.3: The Effect of Pitch [13]

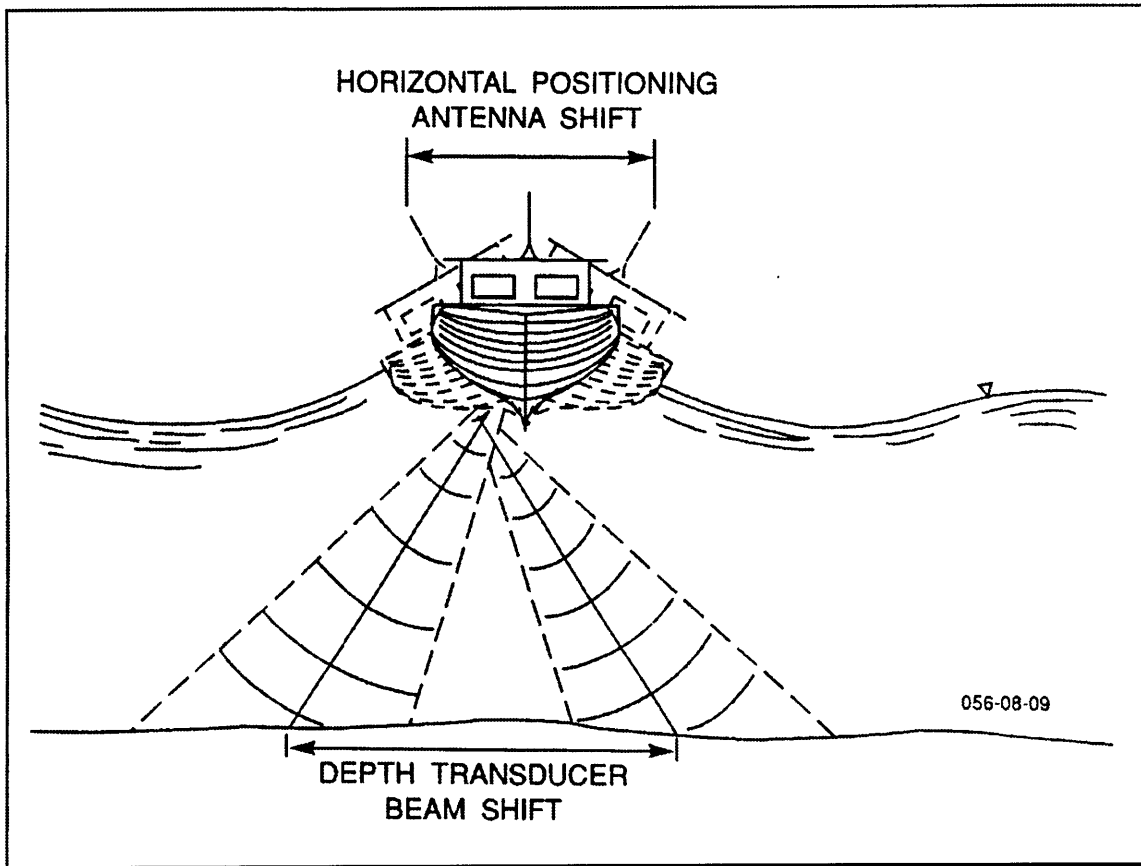


Figure 2.4: The Effect of Roll [13]

In Figures 2.3 and 2.4 it can be seen that the movement of the vessel causes both the positioning antenna and the depth sounder beam to move from the exact vertical alignment which the survey is attempting to measure. The roll and pitch motions can be eliminated from the depth data provided that the angles of roll and pitch are known. The heave motion causes a vertical displacement of the vessel and consequently causes an error in depth measurement. This can be eliminated if the distance the vessel rides up is known.

There are no specific standards for how accurately the specific vessel motions must be recorded. The USACE specifies that for roll or pitch greater than 10 degrees, and for heave of greater than 0.3 feet, vessel motions must be accounted for [13]. These measurement of the vessel motions must then be

included in the calculation of the total depth. Rather than impose standards for the accuracy of the motions measurements, the USACE simply imposes the depth accuracy requirement described above. Accounting for vessel motions is a complicated task which requires the use of sophisticated instruments. The common methods of recording vessel motions are described, shortly.

2.2.4 Tides

Just as the surveyor needs to know the horizontal position of his measurements, the vertical reference datum must also be determined. As with the horizontal case, there are vertical datums which have been developed for use by surveyors in the United States. The two common references are the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88). NAVD 88 is the preferred datum because it is a uniform system covering the U.S., Canada, and Mexico. NGVD 29 was never accepted internationally [13]. While taking a position fix, a surveyor can also determine vertical position in accordance with one of these datums.

The primary reason to refer to a vertical datum when taking depth measurements is to account for tides. The USACE defines tides as “the periodic rise and fall of the water in coastal areas resulting from gravitational interactions of the sun, moon, and earth” [13]. The rise and fall of the tides changes the depth of the water in a given position. Therefore, it is important to refer all depth measurements to a common tidal reference. This is facilitated by converting the vertical position recorded (NAVD 88 or NGVD 29) to a common tidal reference. Alternatively, the tide cycle during the survey can be recorded and the resulting depth data can be corrected based on the *in situ* tidal measurements. The results of this type of survey are still referenced to NAVD 88 and a tidal datum.

The tidal datum currently used by USACE is the mean low lower water (MLLW) datum. This is a recent change from a system which included differ-

ent tidal datums for different coastal areas and the Great Lakes. The establishment of the MLLW datum is a result of the National Tidal Datum Convention of 1980 which standardized the tidal datums for the United States and all of its territory. In addition, the tidal epoch in use was updated at this time [13].

The National Tidal Datum Epoch is a specific 19-year period adopted by the NOS as “the official time segment over which tide observations are taken and reduced to obtain mean values (e.g. MLLW) for tidal datums” [13]. Tides must be recorded and tidal datums updated every 19 years because the sea level is slowly rising and mean tides are increasing. Figure 2.5 shows the gradually increasing tides at Hampton Roads Virginia. When the MLLW datum was established for the United States it was referenced to the 1960-1978 tidal epoch. Until that time, the epoch used was the 1941-1959 cycle [13].

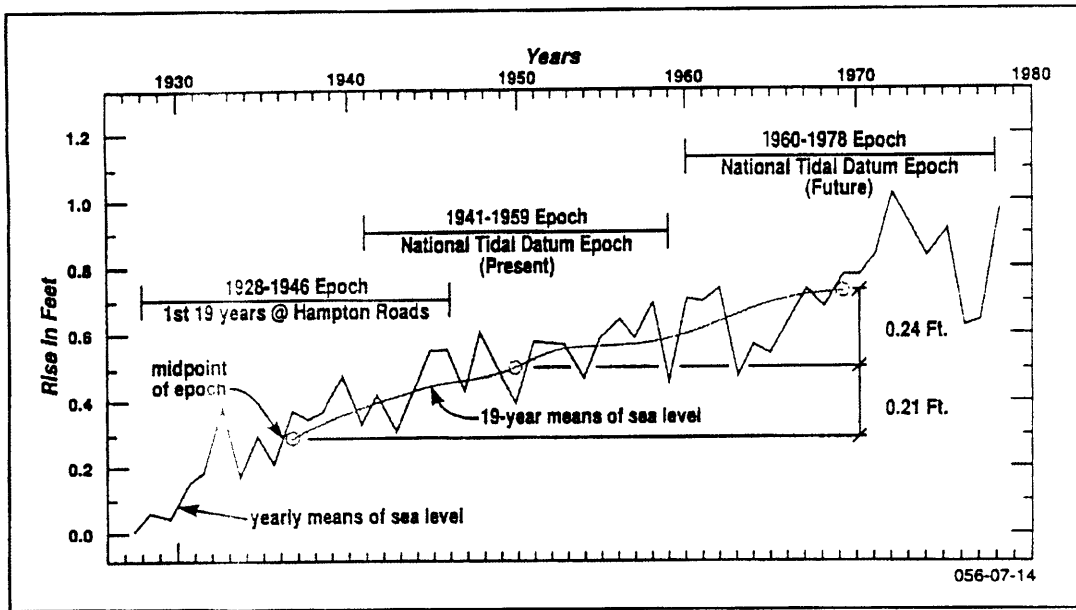


Figure 2.5: The Gradual Increase of Tides [13]

The MLLW datum is used to ensure a measure of conservatism in USACE surveys. By referencing all water depths to the extreme low tide it can be assured that the depths shown on a chart or drawing are the shallowest

possible depth. This is important in navigation projects where the safety of vessels transiting the survey area is at stake. In the case of contract payment surveys, use of the MLLW datum provides one common vertical reference for all calculations.

The actual collection of data used to produce tidal datums is described in section 2.3. The USACE specifications for Class 1 surveys require tidal measurements be taken on site for each survey. This is due to the fact that standard methods of obtaining vertical position are not sufficiently accurate. Therefore, to ensure accurate surveys, the tides must be observed and recorded frequently enough to identify 0.1 foot changes in the level of the water surface. In addition, if wave heights exceed 0.5 feet, a stilling well (described in section 2.3) must be used to maintain Class 1 level of accuracy.

Once the tides have been accounted for, the final adjustments to the depth measurements can be made. By combining data on the state of the tide and the motions of the survey vessel the raw depth measurement can be converted into a final output suitable for plotting on a chart or design drawing. The following section explains the methods currently used to obtain the data types described here.

2.3 Current Survey Methods

To collect the four data types described above, there are many different survey techniques. Not all of the methods used to collect hydrographic data meet Class 1 standards. This section will continue to focus on high accuracy hydrographic surveys, specifically Class 1 type surveys. Therefore, the following sections will describe the methods of obtaining position, depth, vessel motion, and tidal data which are approved by the USACE for Class 1 surveys.

2.3.1 Position Fixes

The art of navigation has a long history. Consequently there are many methods available to determine the horizontal position of a vessel at sea. The three major methods employed by the USACE are tag line, triangulation/intersection positioning, and electronic positioning systems (EPS). Sextant resections and visual ranging are also used by USACE survey teams but only on Class 2 or 3 surveys. Therefore, these methods are not described here. Tag line and triangulation methods are highly accurate but are also manpower intensive. They are slowly being replaced by the use of electronic positioning systems (EPS). This section explains EPS as used by the USACE. Readers interested in other positioning methods are encouraged to refer to [13].

The use of EPS is now the most common method of obtaining position information in USACE hydrographic surveys. All EPS systems use some form of electronic signal to measure the distance between the survey vessel and known points. These electronic signals are broadcast from satellites in orbit or ground stations on the earth. All of these broadcast stations are in well surveyed locations. The EPS receivers measure the travel time to these stations and calculate the range and azimuth to the station. This allows for a fix on the position of the receiver.

Several common types of EPS are the Global Positioning System (GPS) which is satellite based, LORAN-C which uses low frequency electronic signals broadcast from permanent shore stations, and microwave systems which send out high frequency signals from specially erected shore stations. Among these various systems, only a few provide horizontal positions to within 6 meters (2 DRMS) to qualify for use in Class 1 surveys. Microwave systems, with an estimated position accuracy of 1 to 4 meters (1 DRMS) and certain types of GPS are acceptable. To qualify for Class 1 surveys, differentially corrected GPS (DGPS) must be used. DGPS uses both satellites and shore stations to provide position information. DGPS may be of the pseudo-ranging (code phase) or kinematic (carrier phase) variety. Pseudo-ranging DGPS signals are

sent from fixed shore stations operated by the US Coast Guard (USCG) and kinematic DGPS signals are broadcast from specially positioned shore stations. These methods of positioning have accuracy estimated at 0.1 to 5 meters (1 DRMS) [13]. For a general overview of GPS see [15], for DGPS see [16], and for detailed coverage of both systems refer to [17].

Because of the high accuracy of DGPS, and the robust nature of the system, it is the chosen positioning method for USACE Class 1 surveys. When using EPS, of any variety, position fixes must be taken at least every 25 feet or at 1 second, or faster, intervals. In addition to these fix requirements, EPS must be calibrated for use in Class 1 surveys. As the USACE puts it, “no prudent . . . surveyor ever presumes infallibility in survey measurement equipment.” As was mentioned above, careful application of triangulation is often used to calibrate EPS. This method of calibration applies primarily to microwave systems as DGPS “has no prescribed calibration requirements” [13]. The use of DGPS is the most common and best method of positioning currently available to USACE survey teams.

2.3.2 Depth

There are a variety of methods of measuring the depth of water once the position of the surveyor has been accurately determined. Manual methods use a physical device to measure the distance between the water surface and the bottom. Two versions of this are lead lines and sounding poles. While manual methods are extremely accurate, they are also labor intensive so they are not commonly used in USACE surveys. It is more common to use acoustic methods to measure the depth. An echo sounder sends a pulse of sound and measures the travel time of the pulse to determine the depth. A variant of this, which is becoming more common, is the multibeam echo sounder which sends out several pulses to provide a full coverage sweep of the bottom.

Acoustic echo sounders have been in use for many years. The principle is quite simple, as seen in Figure 2.8 below, but there are some factors which must be carefully considered, especially for high accuracy Class 1 surveys. Of primary concern is the speed of sound through the water. This is instrumental in calculating the depth. In actual practice, the speed varies depending on temperature, depth, and salinity. Typically the speed of sound in water varies from 4,600 to 5,000 ft/sec [13]. To account for this variability, the speed of sound must be measured for each particular survey or the echo sounder must be calibrated for each survey.

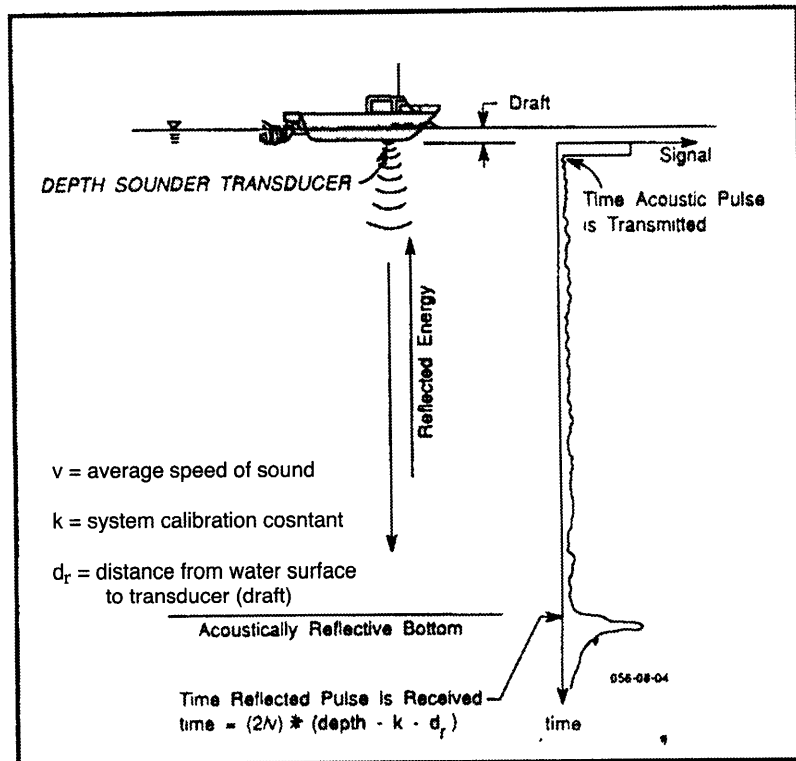


Figure 2.6: Acoustic Depth Measurement [13]

One method of accounting for the variable speed of sound is to use a velocity probe and actually measure this quantity in the survey area. This requires another complicated instrument which can be expensive and difficult to use. To avoid this problem, a calibration technique known as a bar check is

used. A bar check involves lowering an acoustically reflective bar to a known depth directly beneath the depth sounder. The depth output is observed as this bar is lowered through the water column. This process produces a table of the error in the assumed speed of sound for each depth. Typically these depths are recorded at 5 foot intervals. The final calibrated output of the echo sounder is recorded on a continual basis. Typically this is on the order of 5 to 10 depths per second [13]. This represents the densest possible data set allowed by current single beam depth sounder technology.

Multibeam echo sounders have recently been developed which allow a large cross section of the bottom to be observed at once. These systems use special transducers which send out multiple acoustic pulses at once. These are arranged in an angular pattern which provides coverage of a large portion of the bottom. Typically 60 beams 1.5 degrees wide are used to provide a total coverage of 90 degrees [13]. This is portrayed in Figure 2.7.

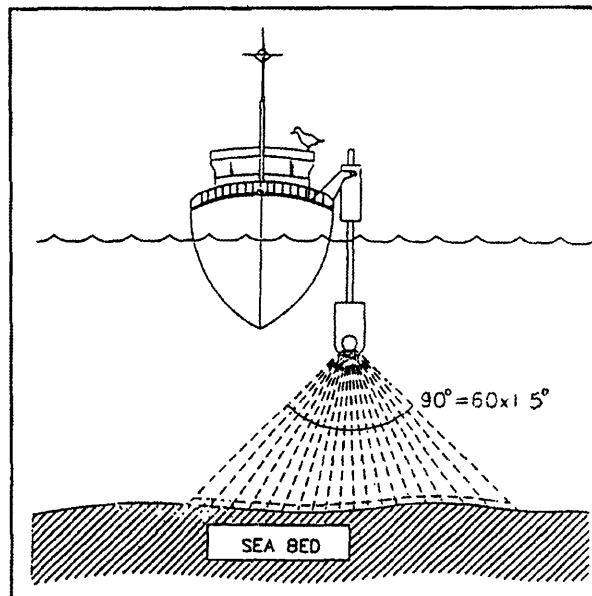


Figure 2.7: A Multibeam Echo Sounder [13]

Multibeam systems are very susceptible to errors caused by the variance of the speed of sound. This is due to the fact that there are multiple travel times being recorded and near the sides of the beam pattern the rays may refract due to differences in the velocity over changing depths. In addition, data

collected by multibeam systems is especially vulnerable to errors caused by vessel motions. USACE standards state that angular motions need to be measured to 0.1 degrees or better if multibeam systems are used. This is a difficult standard for this data and is one reason why multibeam systems are only being deployed slowly [13]. An additional factor is their high cost. A single multibeam unit can cost approximately \$200,000 [6]. Until multibeam systems become less expensive, and vessel motions can be better accounted for, they will be of limited utility and single beam echo sounders will be the depth measuring device of choice for the USACE.

2.3.3 Vessel Motions

Figures 2.3 and 2.4, above, demonstrated how vessel motions can cause errors in the depth and position data recorded by a survey. To compensate for this, USACE survey teams employ instruments which collect data about the vessel's degree of roll, pitch, and heave. These are usually rate gyros and accelerometers. A heave sensor uses an accelerometer to measure the vertical accelerations of the vessel as it rides up and down waves. These accelerations are integrated twice to produce a measure of the vertical movement. Rate gyros are used to record the angular velocities of the vessel as it pitches and rolls. These velocities are integrated to produce measures of angular motion. These types of sensors are useful but several factors in their design and operation should be noted.

One serious problem with these types of sensors is that they must be carefully calibrated. An apparatus to perform a good calibration can be quite complex. The design and construction of such a system is documented in [18]. Even with good calibration at the factory, conventional Motion Reference Units (MRUs) can provide erroneous information. The United States Geological Survey (USGS) has experimented with commercially available MRUs and concluded that for their high precision needs they are inadequate [19]. One source of error in conventional MRUs is attributed to small bias er-

rors in the numerical integrations which can propagate to cause large errors in the final data. An additional problem, is that these sensors measure forces, not actual motions. Therefore, the inertial effects of a vessel moving on the water can be recorded as motions causing the total “motion” data to be in error.

A final problem with these types of sensors is that they do not allow for precise time synchronization of data. This would allow all the data to be saved and carefully examined before final adjustments to the depth measurement are made. Since this is not possible, the data from these sensors is processed in line with the depth data and all that is recorded is a final adjusted depth measurement. This means that any errors in the motion data are rolled into the depth measurement and can not be “backed out” in post-processing.

Despite the assorted problems of MRUs, and their high cost (nearly \$20,000 for top of the line units) they are heavily relied upon when surveying in anything other than flat water. The application of motion recording devices is only used when roll and pitch exceed 10 degrees and heave exceeds 0.3 feet [13]. Frequently a heave sensor alone is used but angular motion sensors are also applied in hydrographic surveys if they are available. Readers interested in greater detail on conventional MRUs are encouraged to refer to [18].

If motion sensors are not available, surveys can only be performed when minimal vessel motions can be assured. This can only be achieved in practice by limiting the sea conditions when surveys may be performed. This is difficult to do because “such limitations are highly subjective and can have significant economic impacts, due either to delayed survey work or inaccurate payment when a survey is performed under adverse conditions.” Additionally, the different conditions influencing the survey quality, including the size and stability of the survey vessel, wind effects, and the direction of prevailing waves, all make a “simple maximum allowable wave height criterion . . . difficult to definitively specify” [13]. Since this option is difficult to rely on, MRUs are used as much as possible by USACE survey teams.

2.3.4 Tidal Data

Tidal data is collected for two purposes. First, it is collected over long time periods to help develop the national tidal epochs described in section 2.2.4. Second, tides are monitored at the site of a survey to ensure that the depths collected in reference to the water surface can be converted to the appropriate vertical datum. This can be MLLW or NAVD 88 depending on the project.

For the purposes of long term tidal monitoring, three types of stations are used. Primary control tide stations are those which maintain continuous tidal observations over the entire 19 year cycle. Secondary tide control stations operate for more than a year but less than 19. Finally, tertiary tide control stations operate for over 30 days but less than a year. These three types of stations are established and monitored by NOS. Based on the data from these stations the national tidal epochs are determined [13].

At a Class 1 survey site, a tide gauge is installed and monitored to record 0.1 foot changes in the water level. An automated tide gauge uses an electronically monitored float to determine the relative change in the height of the water's surface. Since the station is surveyed in relative to a known vertical datum, these changes can be used to reference the overall survey data. If significant wave action occurs at a tide station, its measurements may be in error. To prevent this, a stilling well is used. This is simply a shield installed around the float (or tide staff if manual readings are being made) which damps out the wave action so that a still water surface can be recorded. For Class 1 surveys, stilling wells must be used if wave heights exceed 0.5 feet [13].

The USACE does not specify a particular type of measurement be made to account for tides. As long as tides are recorded on the survey site at 0.1 foot intervals the method used is not considered a vital issue. Frequently this means that an individual can position a marked staff in a known location and at a known vertical position and record the tide over time. Alternatively,

if a project is of long duration an automated gauge can be installed to provide data over the length of the project. Measuring the tidal cycle is the final type of data a surveyor needs to combine depth and position information and produce a chart referenced to known datums. The following chapters describe an alternative method of collecting these types of data.

III) Early ASC at MIT Sea Grant

The work detailed in the following chapters builds on several years of Autonomous Surface Craft research and development. The development of Autonomous Surface Craft (ASC) began at the MIT Sea Grant College Program in 1993. A Freshman Seminar, supported by the Center for Fisheries Engineering Research, used ASC as an ocean engineering challenge to students. The goal of this effort was to develop an ASC which could follow large pelagic fish tagged with acoustic beacons. At the conclusion of the seminar, the ASC effort continued through several Undergraduate Research Opportunities Projects (UROPs) at MIT. By the end of 1994, these UROPs had produced the ASC ARTEMIS, a small vehicle with limited autonomy. In 1995 a research effort began to significantly enhance the capabilities of ARTEMIS. This vehicle served as a testbed and was used for research in navigation, guidance, and control as well as automated data collection.

3.1 The Development and Testing of ARTEMIS

3.1.1 A Simple Testbed ASC

The original ASC prototype, ARTEMIS, is a fiberglass/epoxy 1/17 scale model of a fishing trawler. This model was originally constructed for resistance tests in a tow-tank facility and was configured for autonomous operation by the addition of sensors, actuators, a microcomputer, an electric motor for propulsion, and a servo controlled rudder. The vehicle proved to be well suited as a testbed because of its load carrying capability, agility and ease of operation; requiring only two people to deploy, operate, and recover.

Initial work with this basic platform focused on the development of control systems for the ASC. A microprocessor and digital compass were installed to provide rudimentary navigation and control functions. This configuration used a proportional-plus-derivative (PD) control system to implement simple

heading control. A radio control system provided backup in the event of a computer error. The hardware of the control systems made the radio the default in the event of a failure. In this configuration, during the summer of 1994, ARTEMIS was tested in the Charles River in Cambridge, MA and in Casco Bay, Maine. In the Charles River, simple heading constrained courses were implemented, and in Casco Bay a preprogrammed course which navigated between moorings was successfully completed. These first steps yielded an ASC with limited autonomy but provided a valuable proof of concept. Further details of this work are available in [20].

3.1.2 Control Systems Development and Automated Bathymetry.

The basic ARTEMIS configuration remained static until September 1995 when it became the focus of research into control systems theory. The basic configuration of ARTEMIS was enhanced by the installation of a GPS receiver equipped to receive differential corrections. This provided a highly accurate navigation system and facilitated the development of more complex control systems. A heading constrained waypoint-following controller using fuzzy logic was developed which allowed ARTEMIS to execute basic survey patterns. This control systems is fully documented in [21].

With this new control system it became possible to use ARTEMIS to perform actual data collection missions. The first mission selected was a basic bathymetric survey of the Charles River. To carry out this mission, a simple recreational depth sounder was installed on the transom of ARTEMIS. In addition, a radio modem was added so that the ASC could be controlled in real time and to return the data to shore as it was collected. This radio modem replaced the previous radio control system and provided a "supervisory" capability to the shore operator. To support this type of operation a graphical user interface (GUI) was developed and tested. The GUI, combined with the new control software, allowed ARTEMIS to demonstrate the capability to collect basic bathymetry autonomously. This work is thoroughly documented in reference [22].

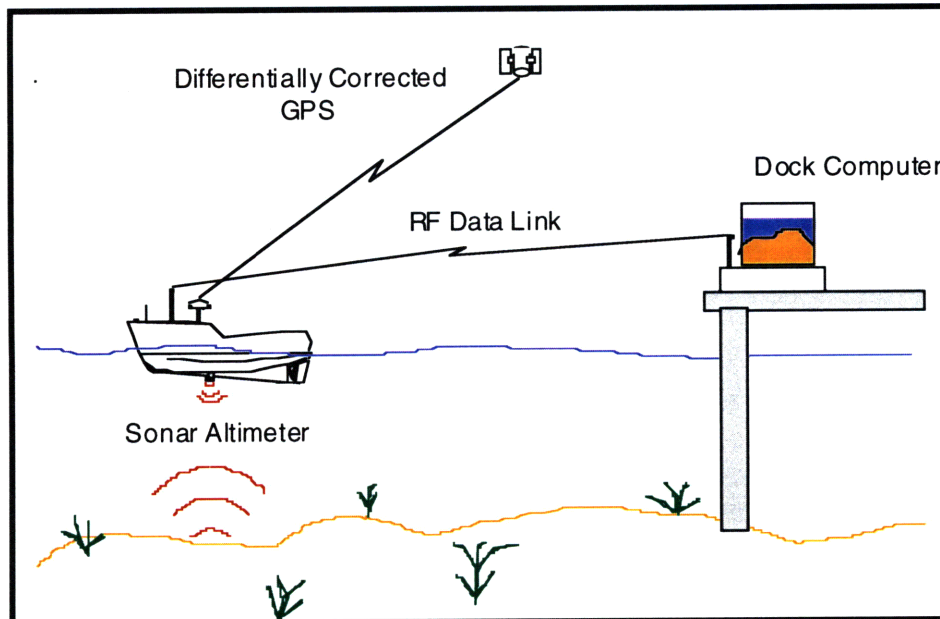


Figure 3.1: Automated Bathymetry Using ARTEMIS

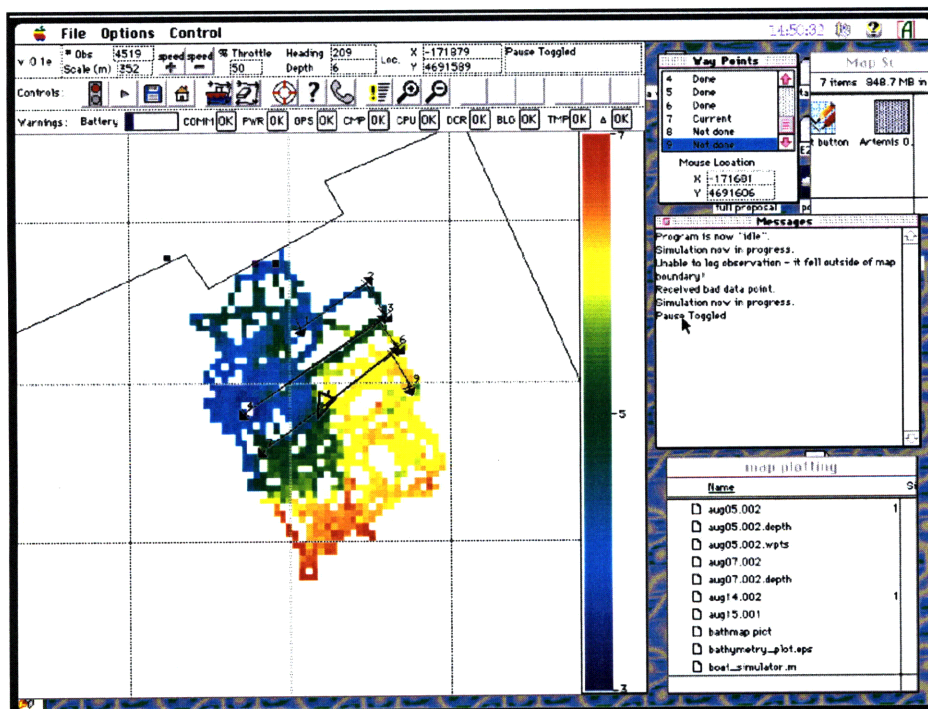


Figure 3.2: A Screen Image of the ARTEMIS User-Interface

Figures 3.1 and 3.2 show a schematic of the automated bathymetry concept and a screen image of the GUI. These developments and a proof-of-concept autonomous bathymetry mission were completed by September, 1996.

3.1.3 Final ARTEMIS Configuration

At the conclusion of the ARTEMIS effort, the utility of ASC had been demonstrated. The final ASC which facilitated the control systems and automated bathymetry research described in section 3.1.2 and in ref. [22] was based on the simple platform developed by undergraduate students. This system was the initial inspiration for the research described in the remainder of this work.

The ARTEMIS hardware was developed from an empty hull. Internally the hull is divided into three compartments, the forward electronics bay, the central battery bay, and the aft rudder actuator bay. The electronics bay houses all of the onboard electronics hardware which includes:

- main vehicle computer and hard disc,
- GPS receiver,
- GPS differential correction receiver,
- digital compass,
- voltage regulation and distribution board,
- depth sounder electronics,
- the thruster motor,
- and the thruster motor controller.

The battery bay of ARTEMIS contains two 12 volt, 24 amp-hour gel cell batteries which are used to power both the electronics and the thruster motor. This configuration has enabled runs as long as four hours before the batteries need to be recharged. Table 3.1, below, presents the specifications of ARTEMIS and Figure 3.3 shows a schematic view.

Length	54 inches
Beam	15 inches
Draft	8 inches
Maximum Displacement	65 pounds
Endurance	2-4 hours
Speed Cruise/Maximum	2 / 2.25 knots

Table 3.1: ARTEMIS Specifications

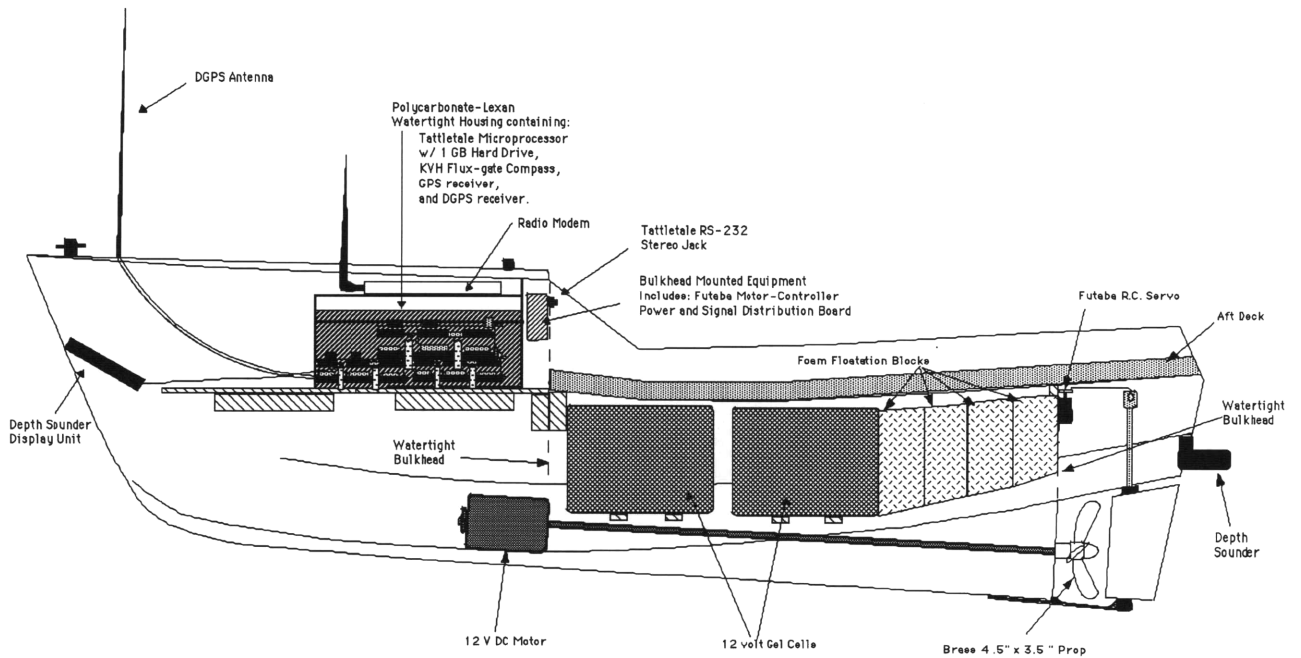


Figure 3.3: The ASC ARTEMIS



Figure 3.4: ARTEMIS in Automated Bathymetry Configuration

IV) Project Goals

The remainder of this document focuses on the specific efforts which grew out of the preliminary research documented in Chapter 3. At the conclusion of the ARTEMIS development efforts, two primary goals were outlined. The first major goal was to develop a new ASC which provided better performance than ARTEMIS. The second goal was to configure this new platform specifically for high fidelity hydrographic surveys.

4.1 The Need for a New ASC Platform

At the conclusion of the automated bathymetry experiments with ARTEMIS, several areas for improvement were identified in the platform characteristics. These are, increased payload, endurance, and speed. A larger payload is desired because ARTEMIS (at 65 pounds) was fully laden and could not accommodate any new instruments or additional batteries. The speed and endurance of the next ASC are based on a desire to create a system as versatile and useful as a small manned vessel. A cruising speed of 5-7 knots and an endurance of 10 or more hours meet these goals.

There is a desire to have the ability of launching an ASC from beach areas or areas with limited accessibility. To achieve this, the ASC's maximum weight was limited to 300 pounds. This limit permits the ASC to be transported, launched, and operated by a two member team. While manned vessels require launch ramps and significant resources, a lightweight ASC can be used in many confined or hard to reach bodies of water and in locations far from marinas or launch ramps. This would allow more coastal areas to be studied.

In addition to increasing the speed, payload, and endurance of the next ASC, better seakeeping is required. This provides the capability to operate in more exposed coastal waters. ARTEMIS could not operate in conditions more

severe than those found on the Charles River. Even there, occasional waves of over one foot were experienced which endangered the vehicle. A new design, which experienced less wave and wind induced motions than ARTEMIS, was called for.

4.2 Configure the ASC for High Fidelity Hydrographic Surveys

In addition to developing a new ASC platform, further work in the development of an automated hydrographic survey system was planned. The basic ARTEMIS tests simply demonstrated the potential of such a system. Outfitting the new ASC with sensors and software to perform hydrographic surveys was the second goal of this effort. The USACE Class 1 standards described in Chapter 2 were identified as the target goal for the survey performance of the new ASC.

To achieve this goal, it would be necessary to account for the four primary parameters introduced in Chapter 2, position, depth, vessel motions, and tide. To make this rather ambitious goal manageable, a process of incremental development was designed. The new ASC platform would first be equipped with the basic ARTEMIS sensor package which recorded only position and depth. This configuration would be tested and its performance quantified. Upon completion of that effort, the additional systems required to meet USACE Class 1 standards would be selected and integrated into the ASC to produce a final configuration which would provide high fidelity hydrographic surveys.

V) The Development of the ASC ACES

As explained in section 4.1, ARTEMIS was not suitable for further use in the development of ASC which could perform useful data collection. A program of development was begun which resulted in the design and construction of ACES (Autonomous Coastal Exploration System). This chapter documents the development of ACES, including its hull, structure, propulsion, and steering, and describes radio controlled sea trials of this new ASC platform.

5.1 Hull and Structure

The first task in the development of a new ASC was to design or select an appropriate hull form. One concept investigated was to modify a small kayak so that it was completely self-righting [23]. This provided a design which would have been robust enough for severe sea states. However, it did not provide enough roll stability for automated bathymetry which was selected as the first data collection mission for ACES.

To provide enhanced roll stability and greater payload, a catamaran was selected as the best hullform for the new ASC. The wide beam and large waterplane area of catamarans reduces rolling motions and increases displacement and therefore payload. This design also had the virtue of providing redundancy in the hull flotation. The failure of one hull would not result in a complete loss of buoyancy. The remaining hull could keep the ASC afloat long enough to be rescued.

An investigation of small hulls which were commercially available led to the selection of the Hobie Float Cat line which offered catamaran hulls in 60 and 75 inch lengths. The maximum buoyancy of the 75 inch hull was 350 pounds. This was more than sufficient given that 300 pounds was established as the maximum gross weight for ACES.

A 75 inch hull was obtained for use as the base for ACES. The framework included with the hull was designed to support a person on a small web seat. This was not an appropriate structure for the mounting of propulsion, steering, navigation, and control systems. A new structure consisting of a modular network of four longitudinal stringers attached to four cylindrical cross bars was designed for this purpose. This structure allowed for flexible mounting of instruments and equipment. Some of the loading bays are designated for propulsion, steering, and vehicle control systems but the others are available to carry instruments or sensors a particular mission requires.

Another feature designed into the structure was a quick release mechanism. This allows the hulls to be removed from the structure so that the entire ASC can be broken down into small pieces for transport to an operation site. A further advantage of the simple mounting system is that different hulls can easily be installed onto the ACES structure allowing various hull configurations to be assembled for long range, high speed, or high sea state operations. Figure 5.1 shows the structure mounted between the hulls.

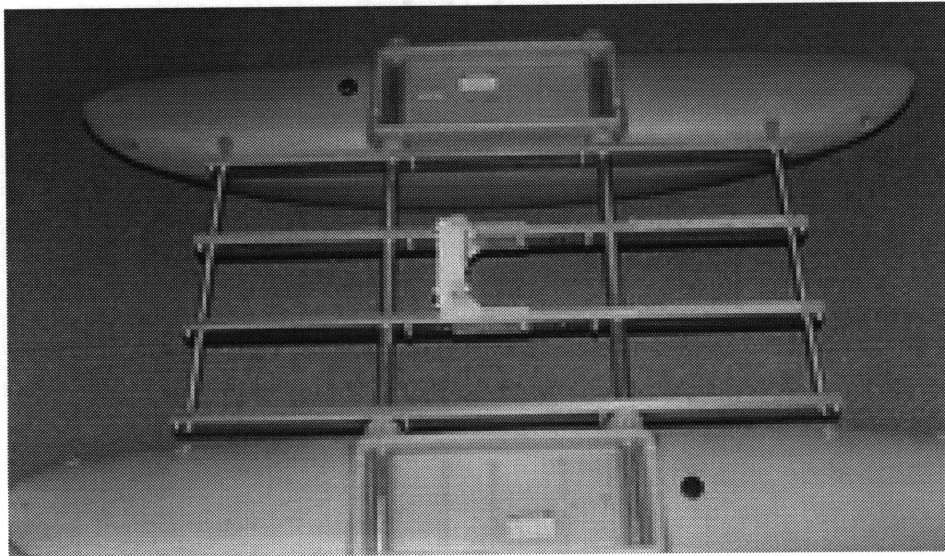


Figure 5.1: The ACES Main Structure

5.2 Propulsion and Steering

Once the hull and structure had been selected, the issue of propulsion and power was resolved. Three options presented themselves; wind, electric-

ity, or internal combustion. Wind was eliminated because autonomous control of sails was too complicated and a vessel propelled by sails would still require substantial electric power for instruments and actuators. A purely electrical system was ruled out by the weight limitation on ACES. An electric thruster and battery system which could provide 5-7 knot speeds for over 10 hours would be prohibitively heavy. Based on these concerns, internal combustion was chosen to provide propulsion for ACES.

A 3.3 hp gasoline engine was selected for installation on ACES. The engine weighs 33 pounds and its fuel consumption rate requires approximately 50 pounds of fuel to operate for 12 hours. For initial testing, electrical power for the computers, navigation, and control systems was provided entirely by batteries. A generator can be installed on the engine to recharge these batteries and make the fuel capacity of ACES the limiting factor on endurance. Limiting the total weight of the power and propulsion system to under a third of the total ASC weight is the primary advantage of using a gasoline engine.

To actuate the engine throttle, an electric servo was used in initial sea trials. This allowed the basic ACES vehicle to be operated by radio control so that performance could be observed without using complicated computer control systems. The autonomous configuration, described in Chapter 6, replaces this servo with a stepper motor. The use of a commercially available stepper motor and motor controller which use an RS-232 interface allowed for easy integration into the autonomous system.

The steering system chosen for ACES, again focused on using simple and easily available components. A rudder mounting point was designed which would hold a sailboard skeg. This permits the use of most commercially available sailboard skegs which come in a great variety of materials and shapes. If a rudder breaks, or does not perform satisfactorily under certain conditions, it can easily be replaced. As with the throttle control, initial sea trials used a servo to actuate the rudder but was later replaced by a system using a stepper motor.

5.3 The Advantages of ACES

The final ACES platform fulfills the requirements identified for the successor to ARTEMIS. Table 5.1 presents the characteristics of ACES.

Length	75 inches
Beam	51 inches
Draft	18 inches
Maximum Displacement	350 pounds
Endurance	12-18 hours
Speed Cruise/Maximum	5 / 10 knots

Table 5.1: ACES Specifications

Table 5.1 reveals that the endurance of ACES is at least three times that of ARTEMIS. The cruise and maximum speeds of ACES are 150 to over 300 percent faster than ARTEMIS. The maximum displacement of ACES is actually greater than the 300 pound limit specified for two person deployments. The weight of the hull, engine, and a 12 hour fuel supply is approximately 200 pounds. This permits a payload of 100 pounds and the hulls provide an additional 50 pounds of reserve buoyancy. These three criteria represent significant improvements over ARTEMIS without significantly increasing the complexity or size of the ASC. The speed and endurance of ACES make it comparable in performance to a small manned vessel.

In terms of cost, ACES is also competitive with small manned vessels. By using off-the-shelf systems and simple construction techniques the cost of the basic ACES platform was kept low. Prototype costs for the platform were approximately \$7500. This includes several systems, such as the servo units used for radio control tests, which would not be needed on a production vehicle. The cost to manufacture the basic ACES platform is estimated at \$4500.

The addition of a control, navigation and sensor suite like that used on ARTEMIS increases the cost to around \$20,000. When compared to the costs of purchasing small boats, chartering research vessels, or deploying multiple fixed moorings the price of an ASC is competitive.

The basic advantages of ACES, including speed, range, and payload were all quantified in the design stages. The goal of increased stability was identified in the design phase and computer aided naval architectural analysis indicated that ACES would exhibit better stability than ARTEMIS. To verify the stability and the expected performance of ACES a series of sea trials were performed.

5.4 Radio Control Performance Assessment

The first goal of initial sea trials was to obtain an impression of the performance of ACES. The speed, maneuverability and Bollard pull (a measure of the thrust available) were all parameters of interest. The stability of the vehicle underway was also an important performance criterion to observe.

Sea trials were run from the MIT Sailing Pavilion in Cambridge, MA. These tests were performed under radio control. A standard hobbyist's marine radio control system was installed to operate the servos which controlled the throttle and rudder mechanisms. The range of this system was several hundred yards which allowed for a wide range of maneuvers.

The vehicle's speed was measured by timing it as it traveled a known distance along the sailing pavilion dock. Idle speed was measured at 1.5 knots and one quarter throttle provided speeds of 3.0 knots. Additional speeds could not be recorded because ACES moved so fast that it was difficult to precisely follow the marked course and obtain accurate measurements. Maximum speed was estimated at over 10 knots.

The difficulty in recording higher speeds was a result of the impressive maneuverability of ACES. Even small rudder angles provided strong turning responses. At low speeds, ACES demonstrated a turning radius of approxi-

mately one boat length (6 feet). This highly responsive steering made it difficult for the operator to maintain a straight course at higher speeds when steering ACES by radio control.. Figure 5.2 shows ACES performing a sharp turn.



Figure 5.2: ACES Demonstrates a Sharp Turn

Measurements of the thrust provided by the engine yielded an explanation for the unexpected performance of the vehicle. A Bollard test was performed with a 20 pound scale. This proved to be insufficient as the thrust produced at full throttle easily exceeded 20 pounds. This large thrust, which was directed straight at the rudder, explained the speed and maneuverability of ACES.

Unfortunately, the thrust produced at high speed caused significant squat. At higher speeds the stern of the vessel was pushed low in the water. This was not a problem at idle or lower speeds so it would not greatly influence any data collection performed at slow cruising speeds. The intended mission

of bathymetric data collection would be significantly influenced by changes in vehicle pitch so correcting the high speed trim was identified as an important area for improvement in the ACES platform.

While high speed operation caused some trim problems, roll stability throughout the trials was good. Visual observation of ACES underway revealed that it did not experience significant heeling motions. ARTEMIS rolled to angles estimated at 15 to 20 degrees but ACES rolled to maximum angles estimated at 10 degrees. This occurred only when the ASC crossed significant powerboat wakes which would have been dangerous to ARTEMIS.

The radio controlled sea trials provided a valuable assessment of the performance of the ACES vehicle. In general, ACES exceeded expectations. Speed, maneuverability, and thrust were all significantly better than was expected. Roll stability was also superior to ARTEMIS. The only negative feature of the vehicle's performance was its tendency to squat while moving at high speed. This new platform proved to be an excellent base for the development of a hydrographic survey ASC.

VI) Autonomous Sea Trials and Preliminary Hydrographic Survey Tests

Once the basic ACES platform had proven to be a good base for a survey ASC, it was equipped with the appropriate sensors and systems to make it fully autonomous. This configuration was thoroughly tested and then equipped with the sensors used by ARTEMIS to perform hydrographic surveys. A test survey was performed with ACES in this prototype configuration to determine how well it could serve as a hydrographic survey tool. This chapter describes these developments.

6.1 Autonomous Systems Checkout

After the radio control sea trials were performed, the rudder and throttle controls were upgraded to stepper motor based systems and the original control programs designed for servo systems were modified to accommodate the new actuators. The primary advantage of using these systems was that they provided feedback about the rudder angle or throttle position which allowed for more precise control over the vehicle. Once these enhancements were made, autonomous operations were planned.

To gain experience with ACES under computer control, the basic electronics package from ARTEMIS was installed. Short term battery and electronics housings were installed so that the preliminary autonomous tests would be easy to run. The microprocessor, a new DGPS receiver, and various power and signal distribution boards were housed in a polycarbonate enclosure mounted to the foredeck. Batteries were mounted in two more enclosures on the port and starboard sides of the engine. A minimal battery set was installed to permit short check out missions.

The field tests of ACES under autonomous control demonstrated that the basic control and navigation systems developed for ARTEMIS were also useful for a larger ASC. Initially, three autonomous missions were run on

the Charles River. The procedure for each mission was quite simple. A waypoint defined course was downloaded to ACES. The engine was started by hand and the vehicle was launched. All three missions were performed at a constant speed.

The first mission was a simple checkout of the ASC systems. A single waypoint was identified and ACES was commanded to navigate to that point and shut down. The second mission added an additional waypoint which defined an out and back course for ACES. This mission was also successful. The final mission was defined by three waypoints and defined a "T" shaped course. Again ACES hit all three waypoints and correctly executed its programmed mission.

These missions demonstrated the functionality of the control and navigation systems which had already been employed on ARTEMIS and the enhanced performance of ACES. In early work with ARTEMIS, the ASC would follow a relatively straight course but would slowly oscillate to either side of its intended heading as it progressed towards a waypoint. ACES, in contrast, followed courses which were remarkably straight and experienced little deviation from its defined course. This improvement may be attributable to the better stability and maneuverability of ACES.

To further evaluate the capabilities of ACES, autonomous missions were run in the harbor of Gloucester, MA. During the summer of 1997 ACES was operated autonomously in varying conditions for a total of over 24 hours of run time. The most challenging conditions ACES was tested under, included four to six foot seas and 30 knot winds. These tests were canceled early due to the discomfort of the support vessel crew. ACES performed well during all of these trials and by the end of the summer had proven to be a reliable and capable ASC. Figure 6.1 shows ACES underway during an autonomous trial in Gloucester Harbor.

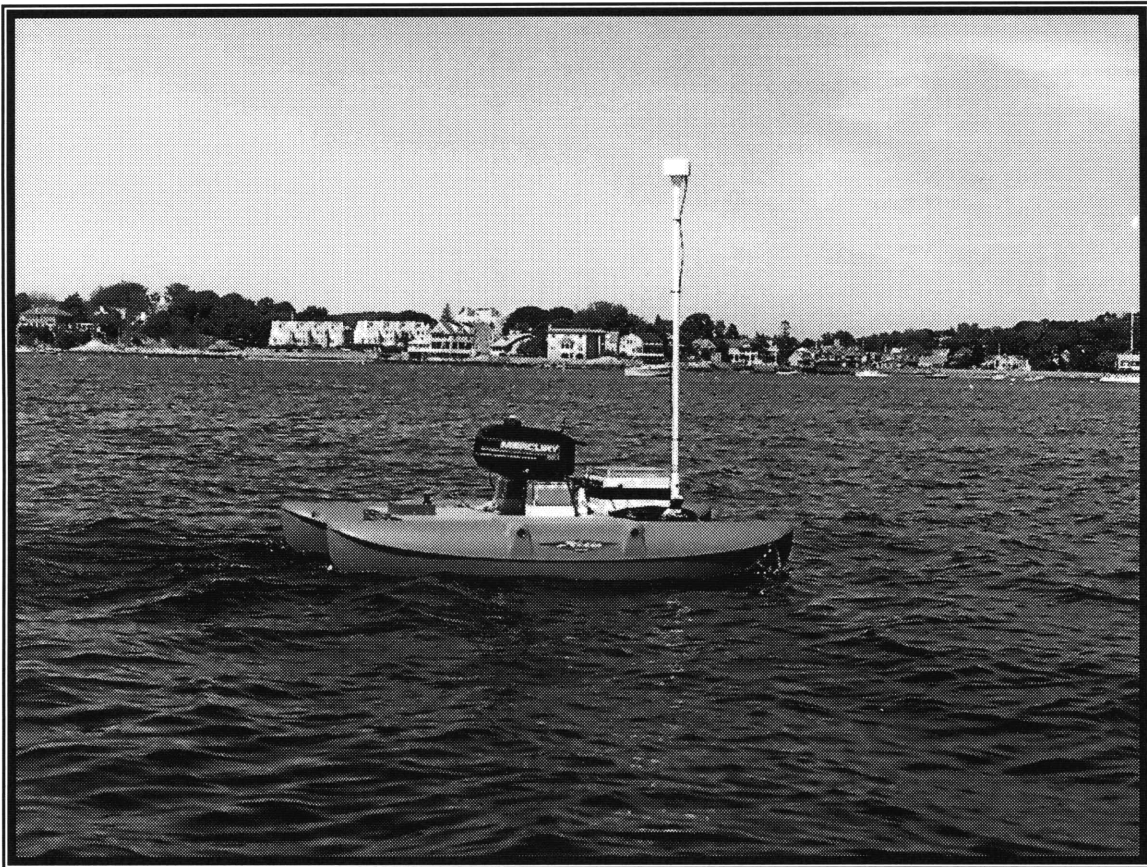


Figure 6.1: ACES Operating Autonomously off Gloucester, MA

6.2 Automated Hydrographic Survey Tests

Once ACES was complete and functioning autonomously, the goal of demonstrating a data collection capability superior to that of ARTEMIS was identified. Conventional hydrographic surveying (as was explained in Chapter 2) is a process requiring measurement of position, depth, vessel motions, and tide. While it is possible to account for all of these with an ASC, it was decided that a preliminary effort should not go to such great lengths. So ACES was equipped with the similar electronics to those employed on ARTEMIS and configured to perform surveys similar to those previously done on the Charles River. To make a useful analysis of the accuracy of ACES as a survey tool, a region which had been previously surveyed to USACE Class 1 standards was selected and surveyed by ACES.

During the summer of 1997 the USACE surveyed the Port of Boston Conley Marine Terminal after it had been dredged. The data from these surveys was obtained from the USACE and ACES was used to perform a survey in the same region. Since the USACE data represented a post-dredge survey it was expected that the bottom topography would be relatively stable. Conley Marine Terminal is in Boston Harbor near Logan Airport. Figure 6.2 shows the terminal in relation to Boston Harbor and Figure 6.3 shows ACES performing the survey.

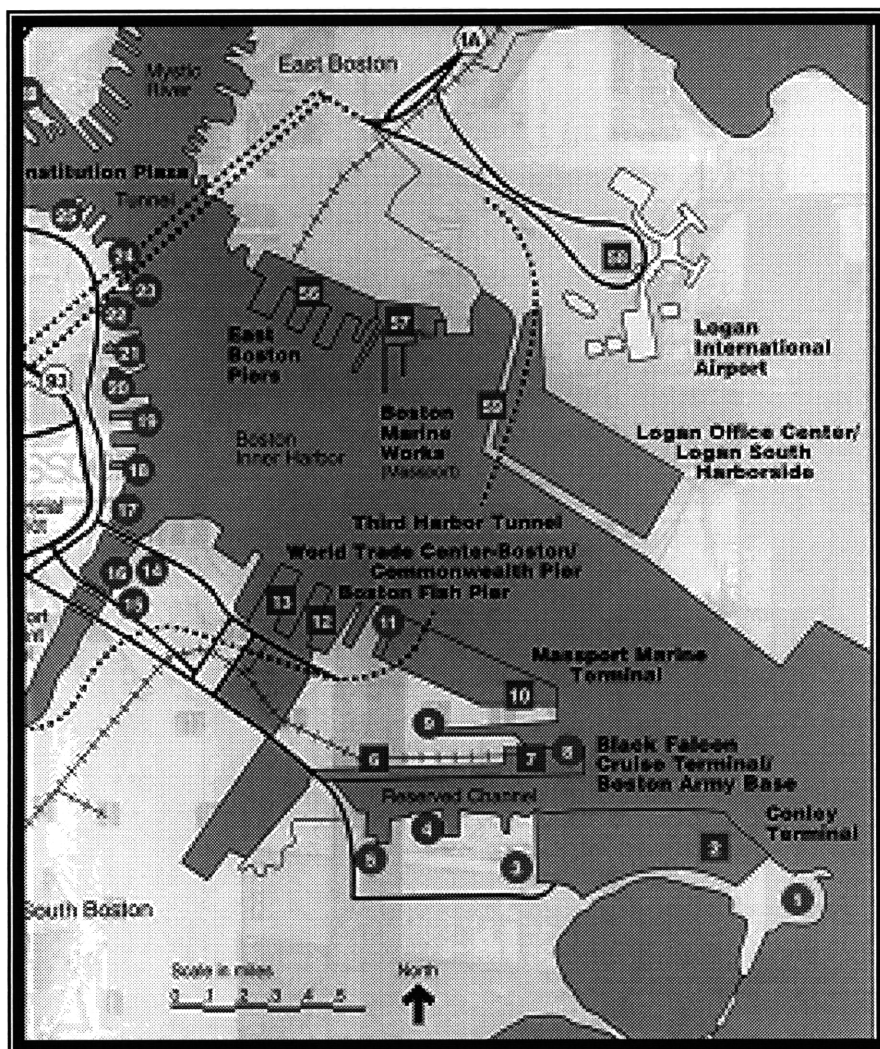


Figure 6.2: Conley Marine Terminal and The Port of Boston [24]



Figure 6.3: ACES Surveying at Conley

At Conley, ACES performed three surveys to cover an area approximately 1500 by 400 feet. Two surveys were run perpendicular to the pier and one was run parallel to it. These surveys yielded a total 23 tracklines and took approximately 45 minutes of total run time. The entire survey process took just under 2 hours on site. After each survey was run, the data was moved from RAM to the hard drive which required an amount of time equal to the length of the survey. This process could be streamlined to permit continuous streaming of data to the hard disk. For the initial surveys it was decided to ensure the retrieval of at least some data, so the runs were broken up and downloaded individually.

ACES collected over 3000 depth and position measurements in the survey area. This region was selected because it covered part of the recently dredged area and part of the bottom which had not been dredged and was therefore shallower. It was expected that these two distinct depth regions

would help provide a better comparison between the USACE and the ACES data. In this same region, the USACE had collected a total of 1288 data points. Figure 6.4, below, shows the points collected by the two surveys. Comparison of these two data sets can provide insights about the performance of ACES as a hydrographic survey tool.

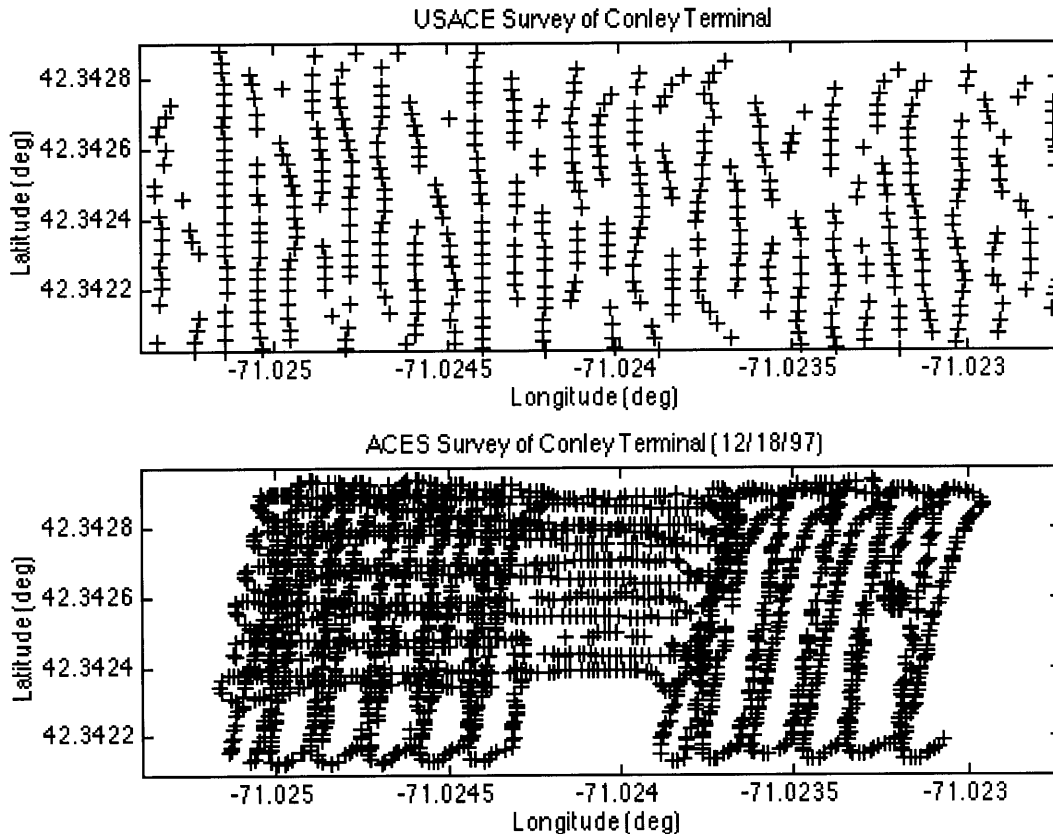


Figure 6.4: The USACE and ACES Survey Data Points

A preliminary inspection of the data yielded results which looked promising. The two data sets were plotted to represent a map of the bottom depth. Figure 6.5, below, shows the two maps side by side. The colorbar represents the depth in feet. To present these results, it was first necessary to account for the difference in the absolute depths caused by tides. Tide was not measured by the ACES survey due to logistical difficulties. To account for the difference in vertical datums between the USACE data and the results col-

lected by ACES, the data was compared and the vertical bias was identified. Each of three ACES data sets was examined and the mean vertical offset from the USACE was found. This was attributed to the tide level and was then subtracted from the ACES data. This offset was close to the height of the high tide (as identified by NOAA tide data) which occurred during the ACES survey. This process provides a reasonable accounting of the tide but it does not account for the change of the tide during the course of the survey.

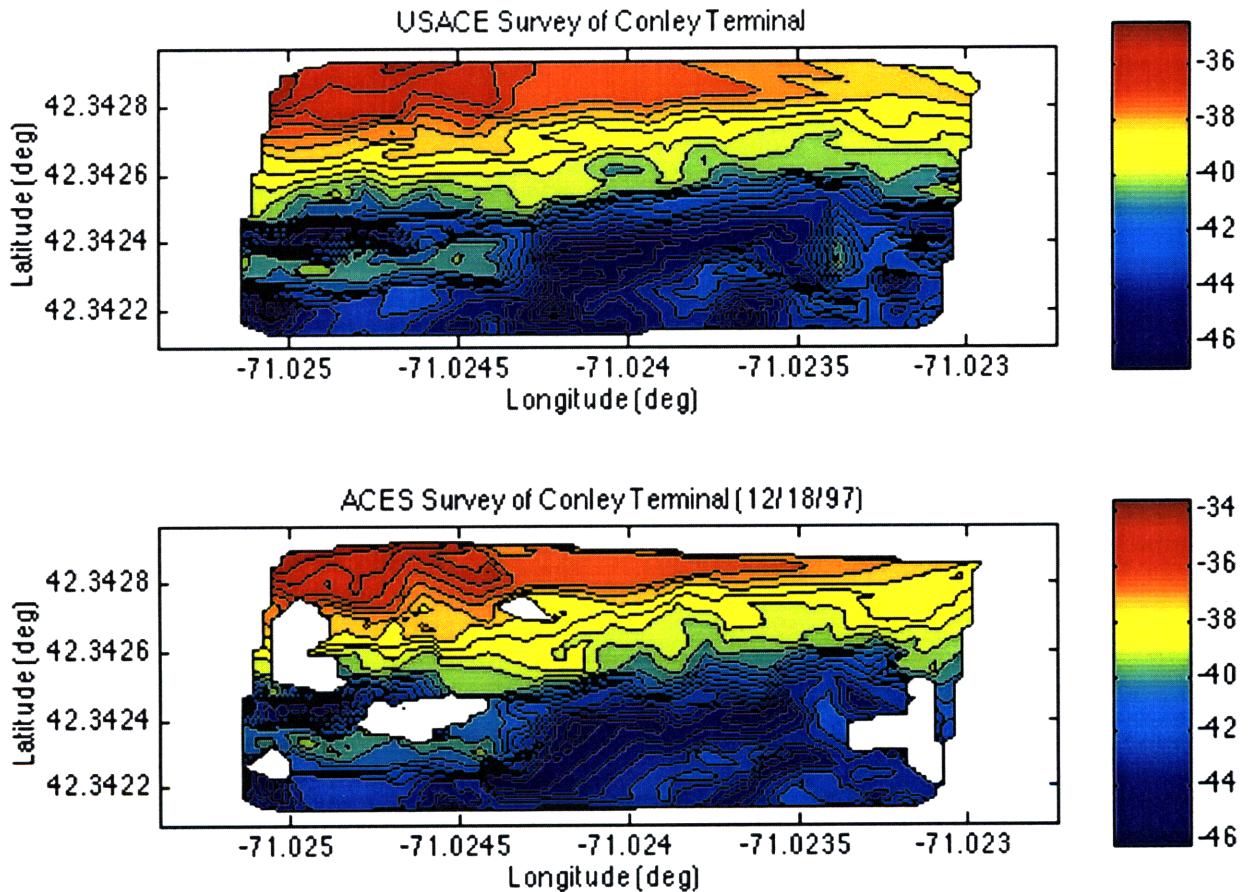


Figure 6.5: The ACES and USACE Survey Data From Conley

The maps in figure 6.5 are a surface mesh fit, using linear interpolations, to the finite number of data points in each set. MATLAB was used to fit the surfaces and plot the maps. The blank spots in the ACES map are areas

where the data was not used because it contained points which were rejected by an outlier identification algorithm. This rejected points which showed significant deviation from their neighbors. There were several sources of errors which could cause these dataless regions.

One source of error was the lack of any record of the vessel motions. The survey was performed on a notably calm day, because motion sensors were not yet installed, but there were still instances where ACES experienced heavy wakes which marred the data. Some of the regions lacking data in Figure 6.5 are attributed to an outlier rejection algorithm which eliminated the very poor data collected in these regions. The cause of this poor data was the wake of passing vessels which caused ACES to experience excessive motions. Without motion sensors, these regions of data were useless and therefore eliminated from the total set.

An additional source of errors in the ACES data was an apparent technical flaw in the depth sounder. For all depths between 41.2 and 42.5 feet no data was recorded. The cause of this error is unknown but is suspected to be a flaw in the depth sounder's timing circuit.

Despite the errors in the ACES data, figure 6.5 clearly shows a good correlation between the ACES and USACE surveys. A more quantitative comparison of these two data sets was desired. This comparison required several steps. Since there was not enough time available to completely recreate the USACE survey only 300 of the USACE data points were in the same region as the ACES survey. Therefore, it was necessary to filter the ACES data to select the points which were geographically closest to the USACE data. This was achieved by dividing the data set into triangular regions defined by the ACES data points. The nearest USACE point found in each triangle was then identified as the geographic coordinate of interest. This coordinate was assigned a depth value computed from the three vertices (ACES data points) which defined the triangular region it occupied. This yielded two sets of 300 data points which had the same geographic coordinates. One set was assigned the USACE recorded depth and the other was assigned a numerical

interpolation based on the three ACES depths nearest to it. The difference in these depth measurements was then be calculated.

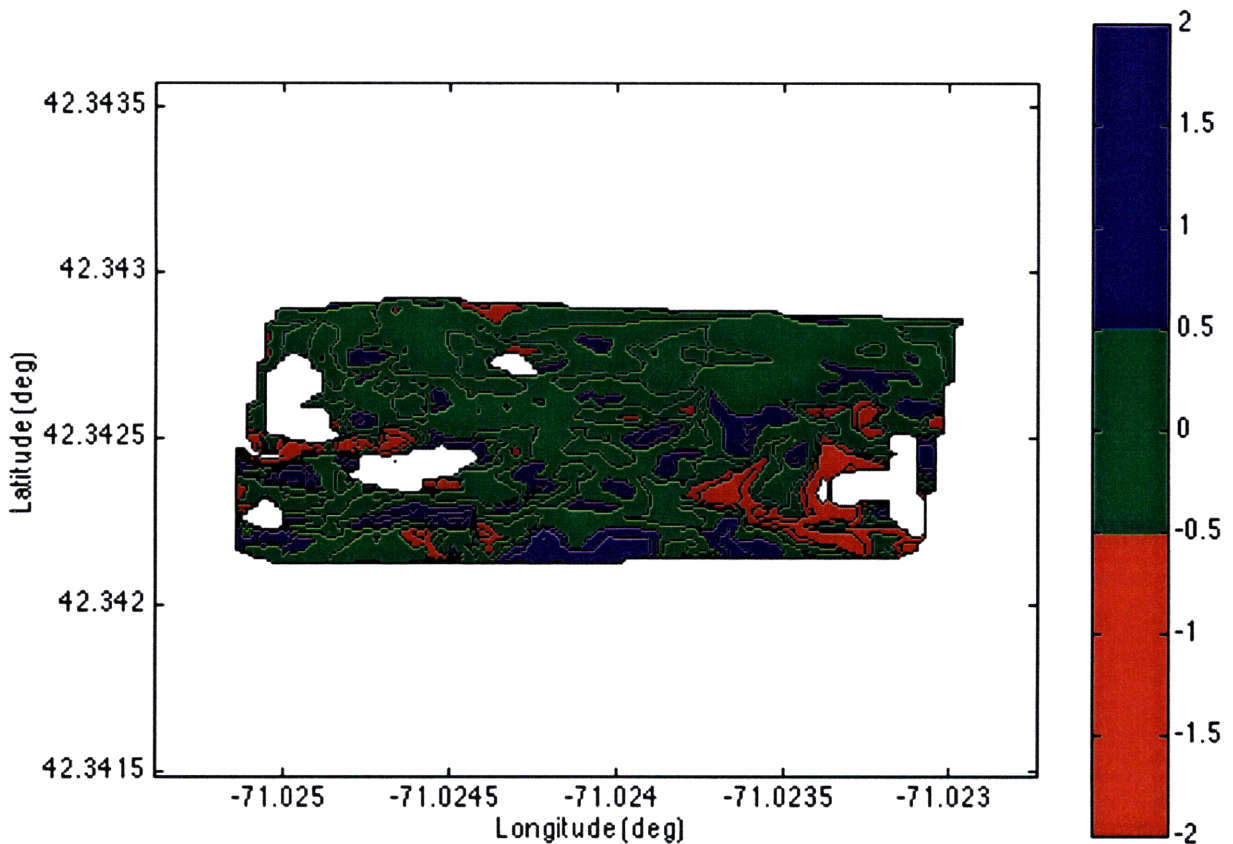


Figure 6.6: The ACES Data Compared to the USACE Survey*

Figure 6.7 shows the difference between the ACES soundings and those of the USACE. Green areas indicate a difference of less than 0.5 feet (Class 1 standards). Red areas indicate where the ACES data is in error and would be dangerous to a passing ship, showing deeper water than actually existed. The blue regions also indicate errors of greater than 0.5 feet but these errors are more conservative than the USACE results and so would pose no threat to

* The MATLAB routine used to generate figure 6.7 is included in the Appendix

shipping. Approximately 78% of the results fall into the green area and can therefore be considered Class 1.

These results were very encouraging given the many sources of error in the survey. Without vessel motions records, using a numerical approximation for the tides, and with a low quality depth sounder, ACES still produced results which met Class I standards approximately 78% of the time. These preliminary trials indicated that ACES most certainly warranted further development and that high fidelity hydrographic surveys using an ASC were possible.

VII) ACES Enhancements

To fulfill the goal of configuring ACES for high fidelity hydrographic surveys, several options were examined and analyzed. This chapter identifies these options and provides details of the final solutions implemented on ACES.

7.1 Depth Sounding

7.1.1 Depth Sounding Options

Several options were identified to correct the problems with ACES' depth sounding capabilities. Replacing the low quality depth sounder with a more sophisticated single-beam echo sounder was one option. Using a multibeam system was also explored. A final option identified was using an Acoustic Doppler Current Profiler (ADCP) to collect depth data. This option at first seemed the most unorthodox but upon further investigation proved to be a viable approach.

To evaluate the different options, several criteria were evaluated. The cost of each option was identified both for an initial prototype and for a volume purchase which would be required if ACES were to be mass produced. The range and resolution of an underwater acoustic system are primarily influenced by its operating frequency and beamwidth[25]. Since acoustic sounders are available in a range of frequencies, their performance was evaluated under several subjective areas rather than by the more quantitative aspects of range and resolution.

The first subjective aspect was "acceptability" to survey professionals, primarily the USACE. This category was meant to encompass concerns including the accuracy and resolution of the instrument. The second category was the "complexity" of the solution. The options selected were either relatively simple systems which are easy to calibrate and use or more complex in-

struments requiring greater effort to implement both initially and in regular operations. The “coverage” of each instrument accounts for the number of data points produced in each survey track-line. Finally, the “versatility” of each option accounts for how useful the instrument would be for missions other than basic hydrographic surveys. These subjective categories were given a rank from 1-5 with 5 being the best possible score. Table 7.1, below, shows the comparison of the various options.

Category	Single Beam Echo Sounder	Multibeam System	ADCP
Production Cost	\$15,000	\$100,000	\$25,000
Prototype Cost	\$10,000	\$100,000	\$0
Cost	3	1	4
Acceptability	5	3	1
Complexity	5	1	4
Coverage	1	5	2
Versatility	1	3	4
Subjective Total	15	13	15

Table 7.1: Evaluation of Depth Sounding Options

While the subjective totals for each option are close, the price of a multibeam system was too substantial for the project’s budget so it was eliminated immediately. Comparing the single beam echo sounder and the ADCP options several points are of interest. Purchasing a typical echo sounder like those used by the USACE obviously ranks high in acceptability. The fact that ACES was already prepared to collect single beam depth data gave this option top marks in complexity as well. The downsides of this approach were its lack of versatility, poor data coverage, and high cost even when a one-time academic discount was obtained from a manufacturer.

Using an ADCP to collect depth data was a novel idea suggested by RDI Inc., a prominent manufacturer of such devices. Representatives of RDI pointed out that the United States Geological Survey (USGS) had already successfully used an ADCP to collect depth data in a reservoir survey [26]. While

this was encouraging, this option still failed to match the proven acceptability of the single beam echo sounder. At the same time, ADCP systems are commonly employed in other fields and are well understood so this option did well in the complexity category. By providing the ability to measure current velocities, and collecting four separate depth records with each survey track, the ADCP did well in the versatility and coverage areas. The final point in favor of the ADCP option was that RDI offered to provide a unit for long term loan. This lack of any significant prototype cost made the ADCP the most attractive option for enhancing the depth recording capabilities of ACES.

7.1.2 The Acoustic Doppler Current Profiler

The ADCP provided by RDI is a sophisticated instrument designed specifically to measure the velocity of water moving past it. This function is achieved by measuring the Doppler shift in a sound pulse transmitted through the water column. The ADCP uses four 1200 kHz transducers angled 20 degrees from the axis of the instrument. Figure 7.1 shows the ADCP used on ACES.

The method by which the ADCP uses these four transducers to measure current velocity is explained thoroughly in reference [27] but is not related to its use as a depth sounding instrument. With the basic ADCP configuration it would be possible to collect the four angled depth measurements and convert them to purely vertical depths using the geometry and the attitude of the vehicle. This is not done with ACES because the ADCP provided by RDI provides a bottom tracking mode.



Figure 7.1: The ADCP used on ACES

The bottom tracking mode uses a software and firmware upgrade to provide the depth beneath the instrument, the speed of the instrument (and therefore the vessel it is mounted on), and a record of travel over the bottom. This mode eliminates the need for the ACES computer to process and record the four different transducer measurements. Instead it receives a depth measurement and the speed and ground track of the ASC. By using the speed and ground track information between GPS position fixes (which are recorded once per second) it is possible to maintain a much better log of ACES' position by dead reckoning (DR). With the electronic compass previously installed on ACES only the direction of travel was measured between GPS updates. Now the ADCP provides both direction of travel and ground speed and therefore better DR information. The bottom tracking mode makes the ADCP both a precise depth sounder and a useful navigation aid.

There are a few drawbacks to using the ADCP's bottom tracking mode to provide depth information. The most important is the relatively short range available for bottom tracking. The ADCP can only provide this mode in water depths of 30 meters or less. This is also the suggested limit for

conventional operation of this particular ADCP. Lower frequency ADCP systems can provide greater depth limits. While this obviously means that this type of sensor cannot be used in deep ocean waters, 30 meters of depth encompasses all of the regions which could be dangerous to even the deepest draft ships. Ports, rivers, and near-shore approach channels all can be surveyed with the ADCP in bottom tracking mode. Another drawback of using the bottom tracking mode of the ADCP is that it eliminates the usage of all four transducers. With four different measurements at 20 degrees the ADCP could provide a small version of a multibeam survey. This capability could be provided by software modifications and is not an actual limitation of the instrument itself.

Installing the ADCP on ACES was relatively simple. A mount was designed and constructed which placed the ADCP under the main electronics enclosure just forward of the engine. This mount kept the ADCP transducers a few inches below the waterline and far enough forward to keep the transducer line of sight away from the propeller or the disturbed water around it which could cause erroneous results. Figure 7.2, below, shows the ADCP installed on ACES.

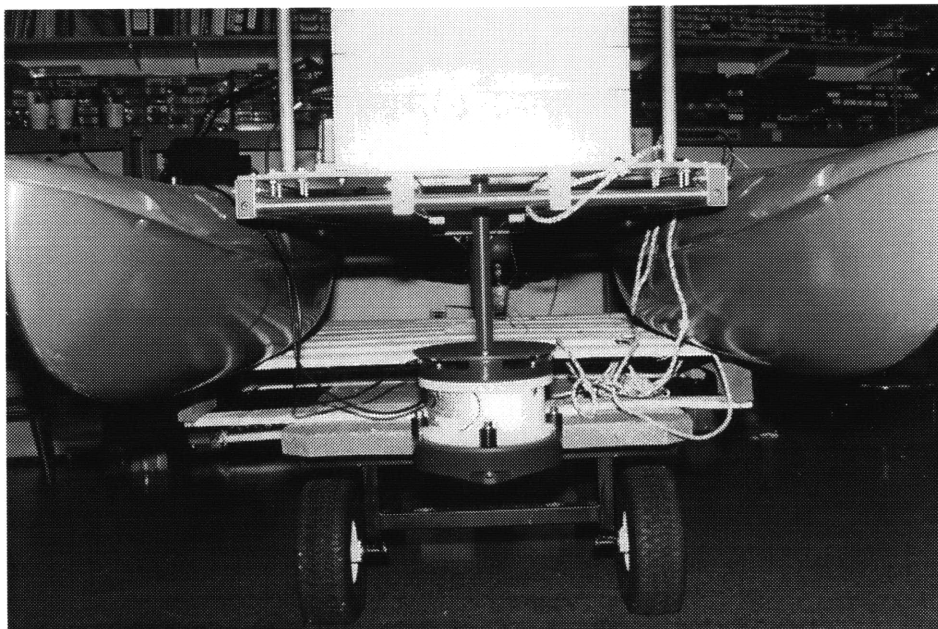


Figure 7.2: The ADCP mounted on ACES

To collect the data from the ADCP it was connected to a serial port on the main vehicle computer and the operating software was modified to collect the new data. Initially, the ACES operating code will not be modified to use the DR information provided by the ADCP. Instead it will log all of the ADCP output which will allow the data to be post-processed and more accurate navigation information can still be provided in the final survey output. Once experience is gained using the ADCP in this mode, the main vehicle control system will be upgraded to use the ADCP data to provide DR navigation between GPS fixes.

7.2 Vessel Motions

7.2.1 Limitations of Conventional Sensors.

The common types of motion sensors, accelerometers and rate gyros, were introduced in section 2.3.3. This section touched on some of the problems inherent in these sensors. There are two primary sources of error when using conventional Motion Reference Units (MRUs). The numerical integrations needed to convert the force measurement actually made by these sensors into motion information can amplify any errors and are especially susceptible to bias errors which propagate and increase through the integrations. Careful calibration can correct these errors so they are not a primary reason to avoid use of conventional MRUs.

A more pressing concern is the role of inertial effects. MRUs do not measure the actual motions of the vessel they are installed on. Rather, they measure the acceleration or angular velocity of the vessel in various directions. On large survey vessels these accelerations and velocities can be converted to useful position information because the accelerations are minimized and do not upset the numerical integrations after calibration. On a small platform, like ACES, which can experience large accelerations and

high velocities, these sensors can not distinguish actual vessel motions. They provide a good source of data on the accelerations but this information can not be accurately converted to measurements of the actual roll, pitch, and heave, at any one instant in time. It is this instantaneous position measurement which is necessary to adjust the depth information recorded on the moving platform. The limitations of conventional MRUs made it necessary to provide a better method of accounting for the motions of ACES during a survey.

7.2.2 Pitch and Roll Measurement using GPS

To record the pitch and roll motions of ACES, an Ashtech ADU2 system was purchased. This system uses an array of four GPS antennas to measure angular motions. A single GPS antenna records position information based on signals transmitted from the NAVSTAR satellites. The accuracy of this position information is degraded by a variety of factors including atmospheric effects and intentional errors introduced by the Air Force (which administers the GPS system) for security reasons. Readers are referred to references [15] [16] and [17] for more information on the theory of GPS. While these errors degrade the absolute accuracy of a GPS position fix, they are essentially equal over the small area of the ADU2 antenna array. This means that the relative motion of the various antennas can be measured very accurately. With a knowledge of the antenna geometry (which must remain rigid), this information can be converted to measurements of the angular motions of the array and the vehicle it is fixed to.

The ADU2, therefore, provides a method of measuring roll, pitch and yaw unaffected by inertial forces. Additionally, it can provide absolute heading information which is free of errors caused by magnetic field variations which commonly disturb compass readings. To provide these various measurements, it was necessary to build an antenna mount which held the four GPS antennas in a fixed position on the vehicle. Discussions with Ashtech

technical support led to the decision to adopt an array with three antennas in line across the bow of the vehicle and one antenna on the centerline at the aft end. This “T” configuration provides the best heading information and still yields good pitch and roll measurements. Figure 7.3, below, shows this antenna array used on ACES.

With the forward antennas spaced 1.14 meters apart and the aft antenna 1.6 meters from the forward antennas angular accuracies of 0.2 degrees can be expected. Since the antennas which are used for heading calculations are on the longer baseline, and because heading accuracy is generally twice as accurate as pitch and roll for the ADU2, the heading information available from this antenna configuration can be expected to have accuracy better than 0.1 degrees [28].

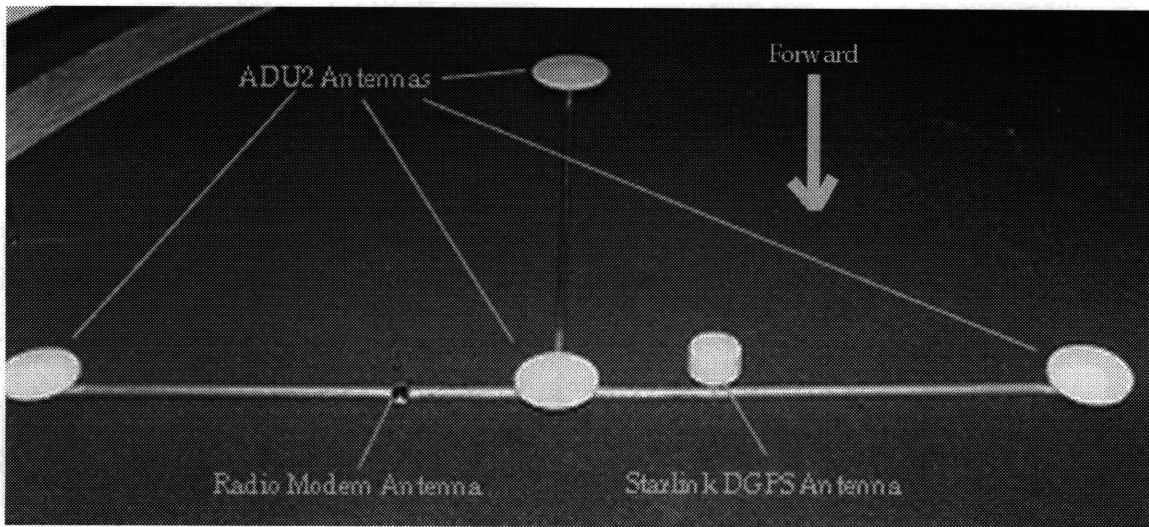


Figure 7.3: The ADU2 Antenna Array used on ACES

The final component of the ADU2 system is the electronics “black box” which houses the hardware required to receive four GPS signals and process them to provide angular motion data. This hardware was placed in the main electronics enclosure on the foredeck of ACES. Section 7.5, below, explains the layout of this enclosure. To collect the ADU2 data the unit was connected to a serial port on the main computer and the software was modified to collect true heading, and pitch and roll in degrees. The ADU2 can also provide

angular velocities, but pitch rate, yaw rate, and roll rate, were not needed to correct the depth information in a hydrographic survey.

7.2.3 Heave Measurements Using GPS

To account for heave, the vertical motion of ACES must be accurately recorded. Basic GPS positioning is not accurate enough for this application. Even conventional DGPS allows for errors of a few meters in vertical position. Again, the reader is referred to [15] [16] and [17] for more details on GPS and DGPS.

To obtain accurate vertical positioning, a kinematic GPS system was selected for use on ACES. The concept behind kinematic GPS is the same as conventional DGPS. The difference is that whereas DGPS uses a series of land stations spread out along the coasts of the United States, kinematic GPS uses a fixed base station very near the area of operations. In addition kinematic GPS tracks code phase information (which can provide mm level accuracy if free of errors) as well as the carrier phase information recorded by conventional DGPS. Just as the GPS errors are nearly equal in the vicinity of the ADU2 antennas, the errors are kept nearly identical in the region near the kinematic GPS base station. Since the fixed base station does not move, and is in a known location, it can record the errors in the GPS signals. These errors can then be removed from the data collected by the moving GPS receiver and its position can be measured with much better accuracy. This process can be performed in real time through a data link. This is known as Real Time Kinematic (RTK) GPS and is a tool which is slowly being applied to Hydrography [29]. Alternatively, the data can be collected and the precise position information can be obtained by post-processing the two sets of GPS data.

To test kinematic GPS techniques to ACES, two Ashtech G-12 GPS receivers were purchased. For future high precision positioning, Ashtech's Z-12 receivers will be used but their high cost precluded use in the prototype. One

receiver is installed on ACES and is used to collect basic GPS data as the vehicle moves through a survey. The other is set up at a fixed, known location and records GPS data during the duration of the survey. These two data sets are then post-processed using GrafNav/GrafNet Version 5, commercially available GPS processing software, to yield precise position information accurate to 0.1 meters. The vertical position accuracy is 0.2 meters. By monitoring the vertical position with this system, the heave of ACES can be recorded and eliminated.

7.3 Position and Tide

The use of kinematic GPS, described above, also provides for very accurate position and tidal data. The kinematic GPS provides better horizontal position data than the basic DGPS installed on ACES. For survey operations the DGPS is used to navigate the vehicle but the kinematic GPS information is recorded for post-processing. With this data, and the corrected depth information provided by the ADCP and ADU2, a chart of the topography of the ocean bottom can be produced. The data collected by the kinematic GPS is referenced to the WGS 84 datum, introduced in Chapter 2. This means that the chart produced by ACES can be referenced to any vertical datums of interest. Tidal information is collected in a survey so that the final chart can be referenced to the MLLW vertical datum. Since the relationship between this datum and the WGS 84 datum is known, using kinematic GPS to measure vertical position eliminates the need for on site tidal measurements.

Therefore, by combining kinematic GPS and the ADU2 system, ACES can record pitch, roll, heave, and tide data. This data can then be combined with the depth information recorded by the ADCP to yield a final hydrographic survey referenced to WGS 84, or any other datum. All of these systems are based on GPS which has been proven to be a reliable and accurate system. Additional advantages of this all-GPS system is that all the various data types can be time synchronized to the GPS reference time and are immune from inertial effects. These features are not available in conven-

tional MRUs. Using GPS and ADCP sensors, ACES is capable of recording all four data components needed in hydrographic surveying; including position, depth, vessel motions, and tidal information.

7.4 Additional System Improvements.

In addition to the primary improvements in the sensor systems installed on ACES, several other enhancements were made during the course of this project. ARTEMIS and the first configuration of ACES used a Tattletale model 7 microprocessor produced by Onset Computers. This system performed well when only a few sensors needed to be monitored. With the addition of the more complicated ADCP and GPS systems it was decided that ACES required a more powerful computer system. A PC/104 computer manufactured by AMPRO was selected as the basis for this system. This computer uses a 166 MHz 486 processor and provides for extensive serial port expansion which was required for the new sensors. This computer is connected to a 500MB hard drive which replaced the smaller 40MB hard drive used previously. This additional computing "horsepower" was installed to provide for smoother operations of ACES as it grew in complexity.

To control all of this new hardware, many software upgrades were required. The basic control systems developed for ACES were maintained. The code required some modification for use with the new processor but retained its basic structure. It is not the goal of this document to examine this code in depth but some basic explanation of the ACES operating system is in order.

The primary control loop runs at 5 Hz. This control loop runs several sub-routines which collect data from the various instruments. Some of the data is used to update the navigation routine which computes the vehicle's position and its programmed course and then executes a Proportional Integral Derivative (PID) controller to command rudder settings. The other data not immediately used by the vehicle is stored to the hard drive. The basic software developed during the ARTEMIS and early ACES projects was upgraded with new routines to collect data from the ADU2, ADCP, and G-12 (or future

Z-12) systems. Readers interested in further details on the software running ACES are referred to [30].

The final system change for this effort was the installation of a radio modem system. The Proxim RS-232 radio link previously used on ARTEMIS was reinstalled on ACES. Early ACES missions used a command tether to communicate with the vehicle to avoid an overly complex prototype. To support this radio link an external 13" whip antenna was installed on ACES. Previously ARTEMIS had used the modem's small standard antenna. With the addition of a 42" omni-directional antenna on the shoreside modem this link provides a 19,200 baud RS-232 connection with a range of approximately 2500 ft. This data link is used to make operation of the ASC easier. Once a mission is downloaded through the radio modem the ASC no longer needs the link but it is available to change the mission or to allow the operator to react to changing situations.

7.5 Final Mission Configuration

The final configuration of ACES represents a complicated assembly of many components. This section presents a summary of the systems installed and illustrates the final vehicle configuration.

Hull: Rotationally Molded Polyethylene Catamaran, Length 73" Beam 52"
Draft 18"

Propulsion: 3.3 hp gasoline engine w/ 7.4" x 6" three bladed propeller

Rudder: Sailboard skeg driven by Intelligent Motion Systems stepper-motor with RS-232 interface

Power: 12 Hawker Energy Cyclon J-Cell lead acid batteries providing 12.5 Ahrs @ 2 volts each for a total system voltage of 24 volts.

Computer Systems: AMPRO 166 MHz PC104 board, 500 MB hard drive,
Proxim 900 MHz RS-232 modem

Sensors: RDI Workhorse ADCP, Ashtech G-12 and Sensor II GPS receivers,
Ashtech ADU2 attitude reference unit, Starlink DNAV-212
differential beacon receiver, KVH C-100 Digital Compass.

The computer systems and sensor electronics are housed in a 15.5" x12"x11" polycarbonate enclosure on the foredeck. The electronic components are held

on two levels. Figure 7.4, below, shows the two levels and the different components.

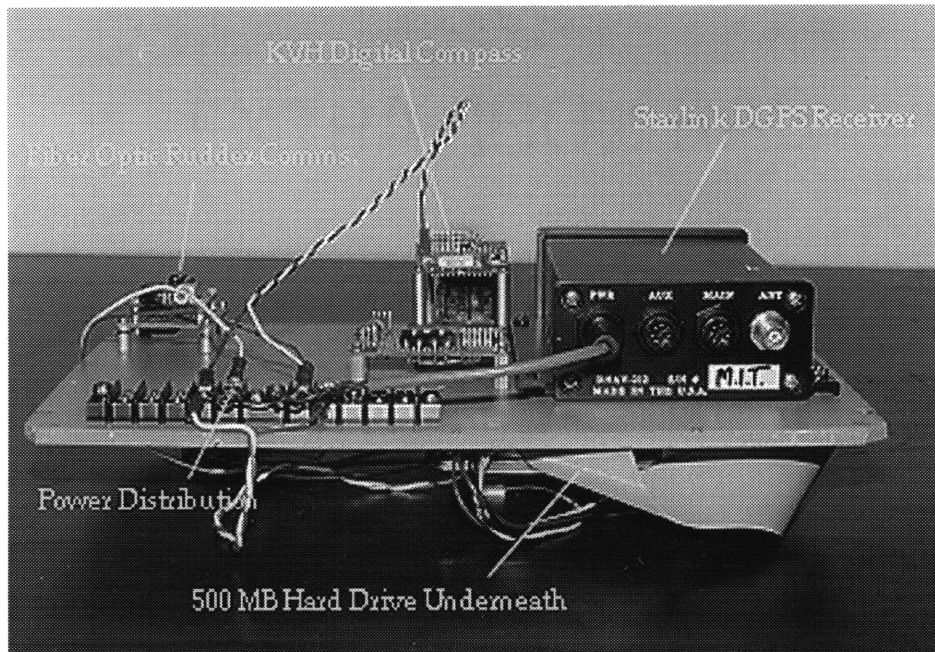


Figure 7.4: ACES Electronics First Level

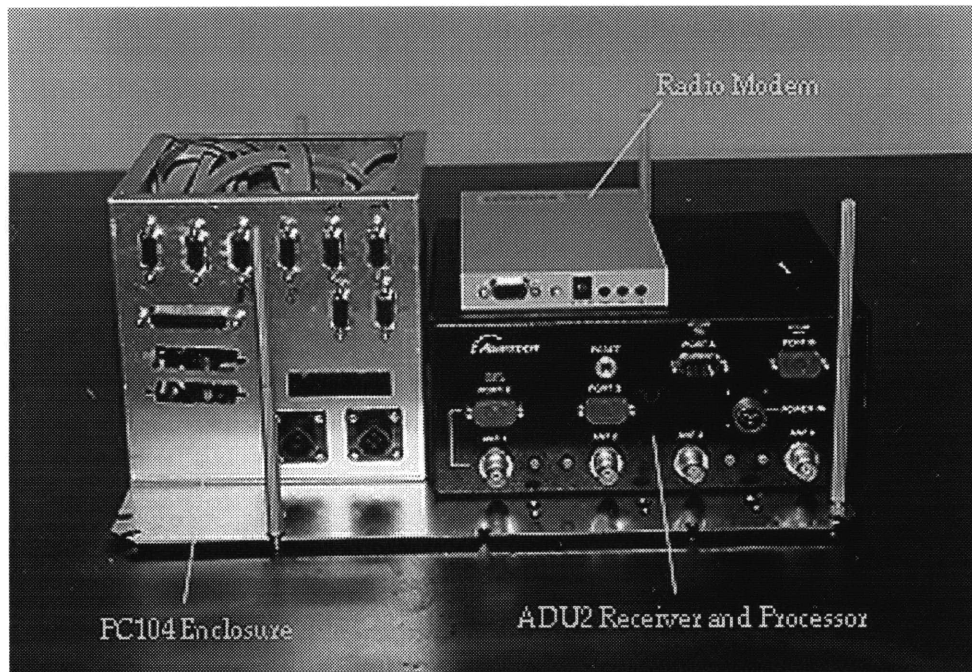


Figure 7.5: ACES Electronics Second Level

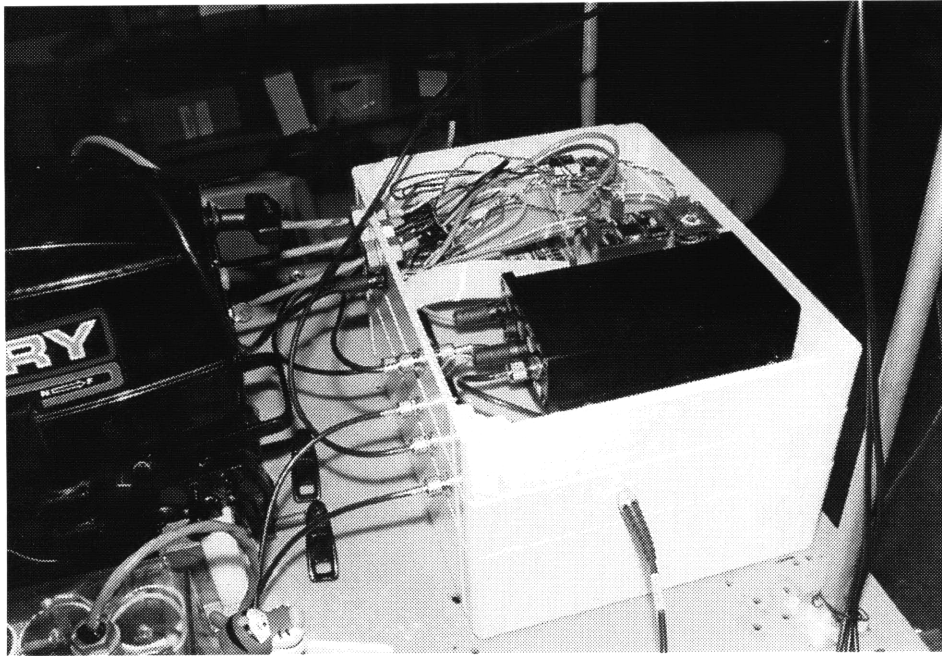


Figure 7.6: ACES Electronics Installed in Deck Enclosure

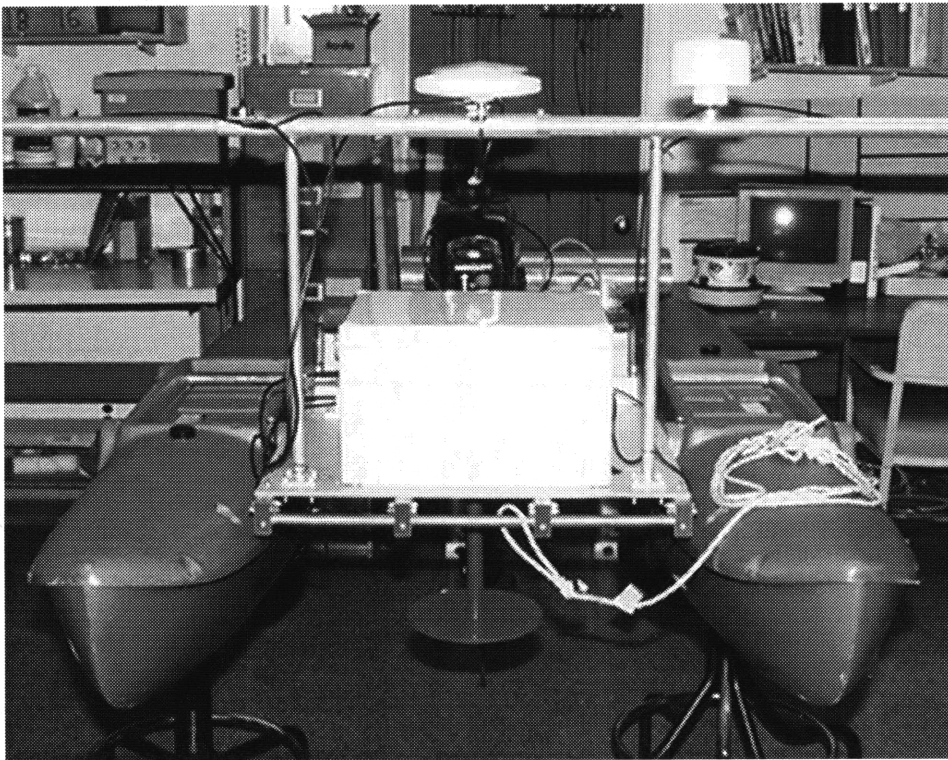


Figure 7.7: ACES Bow View



Figure 7.8: ACES Bow Quarter View



Figure 7.9: ACES Side View

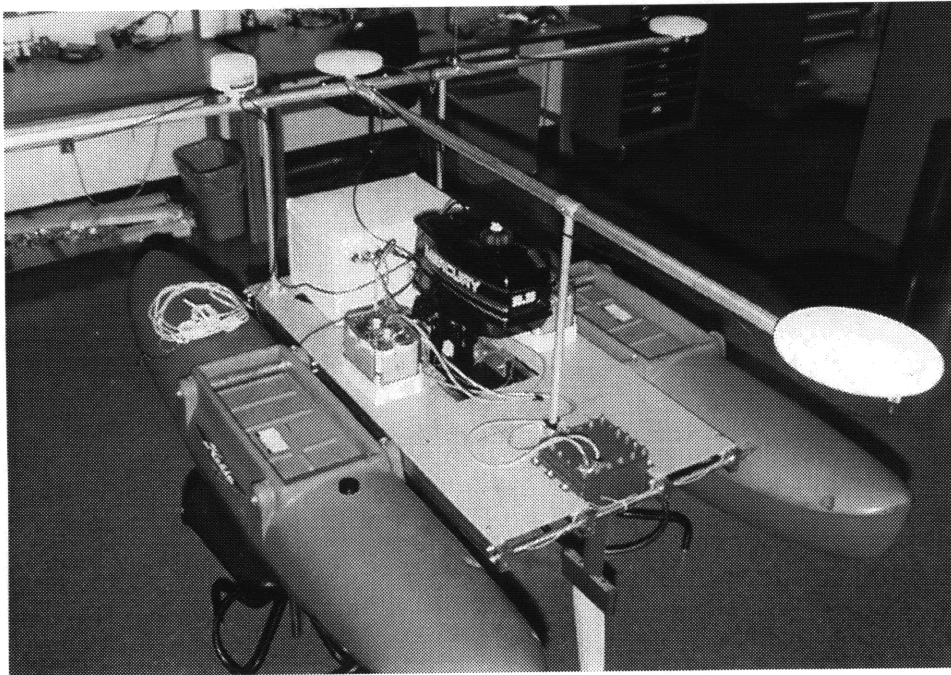


Figure 7.10: ACES Top View

VIII) Vehicle Tests

8.1 Lab Tests

Once ACES was assembled and configured as described above, a series of tests were performed to verify its operation. Initially tests were performed in a laboratory setting to facilitate easy troubleshooting. A three step process was used to examine the systems and ensure that each component functioned properly. The remainder of this section describes this process.

8.1.1 PC/104 Checkout

The first series of bench tests were simply an examination of the functioning of the PC/104 system and its peripherals, including serial communications, user interface (keyboard and monitor), data storage, and power systems. During these tests the PC/104 was powered by a bench supply which allowed the power output of the board to be verified. This step was important so that the hard drive and floppy disk drive which were to be installed would be powered properly and not be damaged. Also, the fiber optic rudder control system was to be powered by the PC/104 card. The output of the card was correct so these systems could be installed in later bench tests.

With the disk drives installed the PC104 card became just like a standard desktop PC. A keyboard and monitor were installed and the ASC could be programmed and interacted with through the MS DOS 6.1 operating system. At this point the translated code from the earlier versions of ACES was installed and verified. At this point the PC/104 was operating just as the old Tattletale based system had.

The PC/104 had been selected because it had the capability of communicating with and controlling several serial devices. At this point the various systems were connected incrementally. The most serious challenge to this was adapting the serial communications from the previous system. The Tattletale

used TTL RS-232 which is based on 0-5 volts with the marked state at 5 volts. The PC/104 required -12 to +12 volts with the marked state at -12 volts. This meant that new interface hardware which both inverted and scaled the RS-232 communications was required. Once this was accomplished, the serial communications of the PC/104 were verified, the entire assembly could be installed and the vehicle systems connected.

8.1.2 ASC Systems Checkout

After the PC104 was tested it was installed in the ASC and all of the systems were connected. To simulate a field operation ACES' batteries were used for all further tests. With the new PC104 system there were no difficulties and the rudder actuator functioned well. The engine control system was also verified and actuation of the throttle valve was confirmed. These were the same systems used with the old computer so it was expected that they would function properly. The PC/104 was able to actuate both control systems just as the Tattletale had.

At this point, all of the basic systems had demonstrated their functionality. Simulated missions were performed which simply commanded the vehicle to "run" by actuating the throttle and servo through a programmed mission. Since the vehicle was stationary, waypoints could not be used to govern these tests. Instead they were based on elapsed time. After these simulations the new ASC configuration was determined to be ready for operation.

8.2 Anticipated Field Tests

While the basic systems checked out in the lab, many of the new sensors could not be verified. The GPS systems need to be in view of the NAVSTAR satellites so they could not be tested indoors. The ADCP could be operated out of water but it is not recommended so that system was also left untested. To test these systems and provide a final demonstration of the new

configuration a series of field tests were planned. Unfortunately, logistical difficulties prevented these tests from being completed at the time of writing. The test plan which was established is outlined here.

Stage 1: Basic Autonomous Operations

This phase of the testplan called for repetitions of the previous missions run in the Charles River. These tests would verify the operation of the new computers in the field using only proven sensors including the KVH digital compass and the Starlink DGPS.

Stage 2: Autonomous Hydrographic Surveys

This stage would bring the ADU2, ADCP, and prototype G-12 GPS receiver on line. For actual scientific or survey data collection the G-12 would be replaced with a Z-12 for superior position data. ACES would be run without using the full capabilities of the Kinematic GPS system to provide an impression of how well it could collect hydrographic data if the highest precision navigation systems were unavailable.

Stage 3: High Fidelity Hydrographic Surveys

The final part of the planned field tests in the Charles River called for the kinematic base station to be set up at the MIT Sailing Pavilion. With the precision navigation system operating, ACES would be used to locate the wreck of a small boat on the bottom of the river. The MIT sailing Master knew the approximate position of the wreck and ACES would provide a high fidelity survey of the river bottom to pinpoint the location of this feature.

This test plan was the only part of the project which was not completed as planned. It is hoped that these tests will be executed soon so that the further experiments outlined in the recommendations below can also be performed.

IX) Conclusion

With the development of ACES, a robust and capable ASC has been produced. Using a combination of commercially available products and custom software and integration systems has provided a platform capable of autonomously operating in conditions up to Sea State 4. This platform can attain speeds over 10 knots and has the potential to operate for 12-18 hours. The size of the ASC is such that it can easily be deployed and operated by two individuals from any convenient beach or small boat. This basic platform can carry scientific sensors and instruments up to a total payload of over 100 pounds.

By adding a simple depth sounder, ACES has demonstrated the ability to perform a hydrographic survey to nearly USACE Class 1 standards. Using basic navigation systems and a low quality recreational depth sounder this platform matched a USACE hydrographic survey (of Class 1 standards) with 78% accuracy. This is a particularly encouraging result given the comparative ease of deployment between the ACES system and a conventional USACE survey vessel. ACES has demonstrated the capability of providing basic hydrographic surveys and the potential to produce high fidelity surveys with appropriate modifications.

The basic survey performance of ACES has been enhanced by the installation of several new sensors. Using an ADCP to collect depth data and a variety of GPS based sensors to monitor position, vessel motions, and tides ACES has been configured to provide high fidelity hydrographic survey data. Using the ADCP provides information to aid in the navigation and control of the ASC, as well as accurate depth data. The GPS based sensors provide the remaining data required for an accurate survey without the problems associated with conventional MRUs. Of particular importance is the elimination of inertial errors which could be substantial on such a small platform.

With the installation of these new systems it is expected that ACES will be able to provide Class 1 or better hydrographic surveys in water depths up to 30 meters and in waters rougher than Sea State 2. While the new configuration of ACES has not been carefully analyzed to quantify its survey accuracy, the manufacturer's specifications for the new sensors indicate that Class 1 or better results can be obtained. Communications with current users of all the systems installed on ACES, including RDI ADCPs and the Ashtech ADU2 and kinematic GPS systems, support this assumption [19].

In conclusion, this research has demonstrated that ASC can be configured to provide high fidelity hydrographic surveys. Experiments with the ASC ACES have verified that low precision systems on an ASC can achieve nearly USACE Class I standards. Additional systems have been installed on ACES and are ready for testing. It is hoped that this newly configured ASC will help meet the growing hydrographic survey needs of the US Army Corps of Engineers and the National Ocean Service.

X) Recommendations

At the conclusion of this research effort it is clear that there are areas for improvement in ACES. Additional experiments to demonstrate its potential are also called for. This section identifies work which is recommended, and in some cases already underway, to further improve ACES. It also outlines some possible experiments which could be used to further quantify the performance of ACES as a hydrographic survey tool.

10.1 Upgrades to ACES

Several subsystems on ACES have been identified as needing additional work. The rudder control system is one example. The current rudder control system has two shortcomings, it is somewhat fragile and has occasionally experienced mechanical failures during use, and it does not allow for absolute knowledge of the rudder position. Before a mission it is necessary to visually ensure that the rudder is centered and confirm this setting in the controller. All future rudder commands are referenced to this initial position.

To correct these problems a new rudder system has been designed. A new control code which uses an optical encoder to continuously track the angle of the rudder has been developed [31]. In addition to tracking rudder angle, this code also substantially improves the response time of the rudder and should provide even better control of ACES. This project also produced a design for a more robust linkage between the actual stepper-motor and the rudder skeg. It is recommended that this new system be installed on ACES.

Another project addressed the throttle control of the gasoline engine [32]. The current controller allows the throttle to be adjusted but does not provide feedback about the engine operating speed. As with the rudder, the system must be initialized at the beginning of each mission and then all ad-

justments to the throttle setting are based on that information. A system which includes a feedback loop based on actual engine speed has been designed. As with the proposed rudder system, this design also provides for a more robust mechanical linkage which will prevent the throttle from getting stuck which occasionally happens with the current system. It is recommended that this system also be installed on ACES.

To provide for longer endurance missions additional fuel and a generator should be provided. A small generator could be attached to the flywheel of the ACES engine. This could be used to recharge the operating batteries and coupled with larger fuel capacity could significantly increase the operational endurance of ACES. External tanks could be mounted on each hull or, alternatively, the hulls themselves could be modified to incorporate large fuel bladders. Estimates suggest that with 16 gallons of extra fuel, and a generator, ACES could operate for up to 12 hours. An additional advantage of installing a generator on the engine is that it could be designed to also serve as a starting motor. Currently ACES is started by hand at the beginning of each mission and if the engine fails it must be retrieved and restarted. A starting motor would allow ACES to respond to engine failures and attempt to restart its own engine. This would also allow the vehicle to shut down its engine and drift (a useful behavior for many oceanographic studies) and then restart and return to shore. While these improvements have not yet been formally designed they are also recommended.

10.2 Additional Experiments

To demonstrate the actual accuracy of ACES as a hydrographic survey tool several experiments are recommended. The first would be to repeat the survey of Conley Marine Terminal. With data collected before and after the ACES upgrades described in Chapter 7, a quantitative analysis of the improvements made to ACES could be produced. The new data could then be

compared to the existing USACE survey to again quantify how well ACES performs in comparison to Class 1 standards.

Once such a demonstration mission has been completed an even more careful scientific assessment of ACES as a survey tool could be made. To perform such an experiment it is recommended that two different types of experiments be performed. First, a false bottom should be created and placed in a carefully surveyed location. With the exact nature of the "bottom" known, a good groundtruth data set can be created. ACES should then be used to survey over this area. The data collected by ACES can be compared to the base data set and the performance of the system could be quantified.

After such an experiment is performed, it is recommended that an area of ocean which experiences large tidal variations be dredged to configure a target region. This region should be selected so that it is entirely dry at low tide. This would allow a precise survey of the nature of the bottom using conventional land survey techniques. Once the tide came in and this carefully surveyed bottom was submerged, ACES could survey the same region and generate a map of the topography. This experiment would demonstrate the accuracy of ACES when surveying actual bottom sediments (as opposed to the artificial bottom previously suggested). With such experiments, the exact level of accuracy of ACES could be measured and its capability of providing high fidelity hydrographic surveys would be decisively demonstrated.

10.3 Further Research

An area in which further research is recommended is the cost of using ASC for hydrographic surveys. High cost is one of the primary challenges facing the hydrographic survey community. It is believed that both the capital and operating costs of ASC are lower than any comparable survey method. A careful investigation to prove this would make the further development and deployment of ASC much easier to justify. Such an investigation should perform a careful cost analysis of the ACES project to account for what

expenses are due to the prototype nature of the project and then determine the total capital cost of mass produced high fidelity hydrographic survey ASC. This investigation should also evaluate the operating costs of such a system. These costs can then be compared to the current costs of hydrographic surveys in near coastal areas. Such a research program is underway but definitive results are not yet available [33]. It is recommended that this research be completed and the results made available to the hydrographic survey community.

XI) Appendices

11.1 Data Analysis Routine

The following is the Matlab routine used to generate Figure 6.7.

```
function compare(lat,lon,depth,square,N)

Lat = lat + 0.00001*rand(max(size(lat)),1);
Lon = lon + 0.00001*rand(max(size(lon)),1);
Depth = depth + 0.5*rand(max(size(depth)),1);

%tri=delaunay(lon,lat);

%figure(1)
%clf
%subplot(1,2,1);
%for i=1:max(size(tri))
%y=[lat(tri(i,1)),lat(tri(i,2)),lat(tri(i,3)),lat(tri(i,1))];
%x=[lon(tri(i,1)),lon(tri(i,2)),lon(tri(i,3)),lon(tri(i,1))];
%d=[depth(tri(i,1)),depth(tri(i,2)),depth(tri(i,3)),depth(tri(i,1))];
%patch(x,y,d,d)
%end

%axis(square);
%axis('equal')
%shading interp

x0 = min(square(1), square(2));
x1 = max(square(1), square(2));
y0 = min(square(3), square(4));
y1 = max(square(3), square(4));

X = x0:(x1-x0)/N:x1;
Y = y0:(y1-y0)/N:y1;

[X,Y]=meshgrid(X,Y);

Z = griddata(lon,lat,depth,X,Y);

ZZ = griddata(Lon,Lat,Depth,X,Y);

%subplot(1,2,2)
%patch(X,Y,Z,Z)
%axis(square);
%axis('equal')
%shading interp
```

```

surf(X,Y,Z-ZZ)
axis('equal')
shading interp
view(0,90)

%j=jet;

%for i=1:5
%    JET(i,1:3) = j((i-1)*12+1,1:3);
%end

c=caxis;
cmin = min(c);
cmax = max(c);

cval = max(abs(cmin),abs(cmax));
Cval = floor(cval)+.5;
if (Cval < cval)
    Cval = Cval + .5;
end

NumDiv = Cval/.5 - 1;

%C = cool(NumDiv);
j=1;
%for i=max(size(C)):-1:1
%    Hc(j,:) = C(i,:);
%    j=j+1;
%end

for i=1:NumDiv
    Hc(j,:) = [0 .2 (.5+(1-.5)*(i-1)/NumDiv)];
    j=j+1;
end

Hc(j,:) = [0 1 0];
j=j+1;
Hc(j,:) = [0 1 0];

%n = fix(3/8*NumDiv);

%r = [(1:n)/n; ones(NumDiv-n,1)];
%g = [zeros(n,1); (1:n)/n; ones(NumDiv-2*n,1)];
%b = [zeros(2*n,1); (1:NumDiv-2*n)/(NumDiv-2*n)];
%H = [r g b];

j=j+1;
%H = pink(NumDiv);
%for i=max(size(H)):-1:1
%    Hc(j,:) = H(i,:);
%    j=j+1;
%end

```

```
for i=NumDiv:-1:1
    Hc(j,:) = [(.5+(1-.5)*(i-1)/NumDiv) 0 0];
    j=j+1;
end
colormap(Hc);
caxis([-Cval Cval])
colorbar
```

11.2 Sample Data

The following is a sample of the data files used to generate Figures 6.5 and 6.7. The first entry is the North Latitude in Degrees Minutes Seconds, the second entry is West Longitude in Degree Minutes Seconds, and the third entry is depth in feet.

42 20 33.97529	071 01 31.89456	-35.9
42 20 33.87247	071 01 31.99521	-35.4
42 20 33.67322	071 01 32.09031	-36
42 20 33.52097	071 01 32.08772	-36.1
42 20 33.38676	071 01 32.07408	-36.7
42 20 33.05060	071 01 32.00575	-38.5
42 20 32.91757	071 01 31.96493	-39.5
42 20 32.80571	071 01 31.93421	-43.3
42 20 32.62336	071 01 31.88896	-43.1

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