

# ORCA - Oceanographic Remotely Controlled Automaton

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## Abstract

The Mapping, Charting and Geodesy Branch of the Naval Research Laboratory at Stennis Space Center, Mississippi, is conducting a multi-year program for the development of unmanned, untethered sensor systems for the collection of tactical oceanographic data in littoral regions. The primary function of this program is the development of immediate force-multiplying survey capabilities for the collection of hydrographic data to support the U.S. Naval Oceanographic Office. This paper reviews the vessel, sensor systems, program progress to date and future plans for a comprehensive oceanographic survey system. The prototype platform currently in use for this project is the ORCA semi-submersible. The ORCA is an air-breathing vessel which travels just below the water surface. In contrast to a full-size survey ship, ORCA is able to collect bathymetric data of the same quantity and quality, but will have one-fortieth the life-cycle costs.

## 1 Introduction

The Naval Research Laboratory (NRL), under a memorandum of agreement with the Naval Oceanographic Office (NAVOCEANO), is developing the first generation of the **O**ceanographic **R**emotely **C**ontrolled **A**utomaton (ORCA). The mission of the ORCA is cost effective collection of routine hydrographic survey data. Acting as a “force multiplier” the vehicle will address worldwide survey requirements. Through combined funding from NAVOCEANO, the Center for Tactical Oceanographic Warfare Support (TOWS), NRL and ONR, the Mapping, Charting, and Geodesy Branch (MC&G) of NRL at Stennis Space Center, Mississippi is conducting the development of two ORCA systems. C&C Technologies Inc., in Lafayette, Louisiana, has performed the vessel modifications and has developed the integrated sensor and communication systems for ORCA.

The ORCA uses a semi-autonomous air-breathing vessel for sensor deployment, shown in Fig. 1. The vessel travels just beneath the surface using an above water snorkel for air intake, and has active attitude control to minimize platform motion, which is essential for acquiring accurate multibeam data. With this design, ORCA’s stability matches that of much larger platforms (70+ meters) making it ideal for the collection of many forms of oceanographic data. The first prototype of this vessel was originally made by International Submarine Engineering (ISE) Ltd. in 1983 [1]. The two vessels being used for this project were originally denoted “Sea Lions”, manufactured for NRL in 1985 by ISE. In 1991 the Canadian Hydrographic Service (CHS) fielded a later generation of this vessel, known as the DOLPHIN, equipped with a Simrad EM100 bathymetry system [2]. This system configuration is currently in use by CHS through their primary surveying contractor Geo-Resources, Inc.

In 1992 NRL’s MC&G Branch evaluated the CHS system [3] which ultimately led to the U.S. Navy’s ORCA project. A primary consideration leading to this project was the projected cost savings over the use of standard hydrographic vessels as determined by Dinn et. al. [4]. A joint NRL/NAVOCEANO cost analysis determined that the ORCA will have one fortieth the life cycle costs of a full-size survey vessel, yet it is able to collect bathymetric data of the same quantity and quality. The ORCA vessel has been substantially changed from its original Sea Lion configuration, and the Simrad EM950 multibeam sonar is its primary sensor.

The planned operational scenario for the first generation ORCA is the collection of bathymetry and acoustic imagery in water depths up to 300 meters. The EM950 has a wider swath width than the EM100, and has the additional capability of providing collocated acoustic imagery of the seafloor. The first two ORCA systems are scheduled to be completed during fiscal year 1995, at which time one system will be delivered to NAVOCEANO, the primary Navy command for the collection, archiving, and distribution of oceanographic data. They will develop methods for ORCA deployment from: the new T-AGS 60 class survey

ships; vessels of opportunity; and pier side. The second vessel will be retained by NRL for further system development and additional sensor integrations.

Bathymetry and acoustic imagery represent fundamental characteristics of the ocean environment which directly impact near-shore naval warfare activities such as mine and amphibious warfare. Regional conflicts have repeatedly demonstrated the need for these basic data and the consequences of their absence. Reliable bathymetric data has been found lacking in many conflicts; recent examples being Operation Desert Storm in the Persian Gulf, relief efforts in Somalia, and the restoration of democracy in Haiti [5]. With current assets, NAVOCEANO has a 360-year backlog of coastal surveys in politically accessible areas [6]. Bathymetry primarily provides essential data for safety of the navigation in a region, but it also provides detailed information about seafloor morphology. Acoustic imagery can provide a rudimentary indication of seafloor composition and acoustic response.

## 2 Vessel Alternatives

The mission of ORCA is the cost-effective collection of hydrographic and oceanographic data. To carry out this mission it must be able to rapidly survey large areas. This requirement mandates relatively fast surface or near surface vessels with swath sensors of sufficient power to reach the seafloor. Data types that are viable for this mission include bathymetry, acoustic imagery, current profiles, sediment classification, surface water temperature, and surface optical properties of the water. Traditionally, these surveys have been executed using surface craft, which suffer from entrained air bubbles passing over the transducer faces, resulting in higher noise levels and reduced sensor ranges. Small craft are particularly affected by this, and have the additional disadvantage of poor stability which heavily degrades the performance of vertical reference units. Large survey ships reduce the stability problem but have high life-cycle costs.

The most restrictive vessel requirements are imposed by hydrography. The bathymetry data collected by ORCA will ultimately be placed into Defense Mapping Agency (DMA) databases for general distribution. As a result, the bathymetry data must meet International Hydrographic Organization (IHO) standards. In Special Publication No. 44 (1987) the IHO has established bathymetry standards requiring: 1) depth accuracy of 0.3 meters for depths from 0 to 30 meters and 1% for depths greater than 30 meters for at least 90% of the data; 2) Positional accuracy of 0.15% of the chart scale, for a 1:5000 chart this corresponds to a required accuracy of 7.5 meters. Complying with these accuracies requires the use of state-of-the-art bathymetry sensors, positioning systems and vessel attitude systems.

To meet the low cost and stability requirements, candidate vessels are semi-submersibles and submersibles. Table 1 compares the two vessel technologies as applied to this mission. The exposed mast on the semi-submersible allows radio transmission for real-time data and vehicle control plus the use of differential GPS (DGPS) systems for accurate positioning. Real-time data and control is a significant element, as sophisticated survey instrumentation is typically designed to be operated with a human in the loop. Real-time data and control can be achieved with a submersible by using a signal-only tether, but this restricts its range and speed.

Both vessels offer the advantage of stability, but a semi-submersible's performance will ultimately be degraded in sufficiently high sea-states. A semi-submersible offers key advantages of payload size, long duration, electrical power and speed. As a consequence many off-the-shelf sensors are readily deployed with such a vessel. Duration, power, speed, and payload size continue to be drawbacks with submersibles, increasing overall survey cost. The ORCA vessel has proven difficult to launch and recover in contrast to most submersible designs due to its mast and keel configuration. Perhaps the most outstanding disadvantage of a semi-submersible is the fact that it is a potential hazard to surface craft navigation. This is a key advantage of a submersible, but the submersible must contend with a 3-dimensional vice 2-dimensional navigation problem. Accurate water column sound velocity profiles must be obtained for the collection of bathymetry data with multibeam systems; a possible advantage of a submersible over a semi-submersible is that it could navigate vertically to obtain its own sound velocity profile data.

NRL chose to proceed with a semi-submersible design primarily because it already possessed two Sea Lion vessels. In retrospect, and considering available submersible technology, this was the most effective approach. Overall power and size requirements of current off-the-shelf sensor systems capable of executing the mission have been restrictive. The power draw of the present sensor package is about 35 amps at 24 volts, and many of the sensors had to be repackaged to fit on the enlarged Sea Lion vessel. In most cases, sensor systems were 'split' such that the transducer and transmitter/receiver electronics are located on the vessel,

	Semi-submersible	Submersible
Real-time data & control	++	+
Stability	+	++
Mission duration	+	-
Speed	+	-
Launch & recovery	-	+
Electrical power	+	-
Sound velocity profile	-	+
Off-shelf sensors	+	-
Navigation Hazard	-	+
Accurate Positioning	+	-
Payload Size	+	-
Navigation	+	-

Table 1: Comparison of vehicle technologies

and the data processing, control and display systems are located on the host ship. Significant engineering challenges had to be overcome just to allow the sensor systems in their present configuration to contend with the time delays imposed by the communications link. Elimination of the communications link between the vessel and topside portions of these systems would require extensive software development. NRL plans on using the lessons learned from the ORCA development to incrementally tackle the obstacles for fully autonomous survey operations, and to ultimately transition these systems to submersibles once the vessel technology is sufficiently mature.

### 3 ORCA Vessel

The current ORCA configuration is shown in Fig. 1. Its overall length is 7.7m, and the main hull diameter is 99cm. Total height is 6.3m from the bottom of the keel to the top of the mast. The system's antennas extend another 2.7m above the top of the mast. Total vessel weight is approximately 4500 kg, including the sensor systems. There are two large dry compartments, each accessed through a hatch on the top of the vessel. The forward compartment contains the vessel control computer and sensor electronics and the aft compartment contains the propulsion plant. Each compartment contains a water level sensor and bilge pumping system. The propulsion plant is a 150 h.p. Sabre diesel engine, with air intake at the top of the mast and submerged exhaust at the top of the aft vertical fin. The engine drives a hydraulic pump providing power for all maneuvering surfaces. The engine also drives a 24-volt, 100-amp alternator which provides ample electric power for the vessel and sensor systems. The standard vessel configuration allows speeds up to 12 knots, and it can be fitted with a lower pitch propeller and larger control planes for 6 knot operations. Sea-pressurized bladders contain 378 liters of diesel fuel allowing 24-hour continuous operation at 10 knots. When surfaced the vessel has a 2.1m draft. It is positively buoyant and is 'driven' below the surface; underway draft is operator selectable up to 6 meters.

The ORCA control system is shown in Fig. 2 and is generic to the 1989 vintage ISE DOLPHIN control system. Vessel control is accomplished with a MC68010-processor based GESPAC computer system on board the vessel. Vessel orientation and motion are determined by the vessel control computer using several on-board sensors: pitch inclinometer, roll inclinometer, three-axis angular rate sensor, vertical accelerometer, depth sensor, plane-position sensors and a gyroscope. Vessel maneuvering is accomplished through the use of bow planes, stern planes and a rudder. The bow planes control depth and roll, the stern planes control pitch and the rudder controls heading. The GESPAC also controls engine speed and monitors its temperature, oil pressure, and alternator output.

An AT-PC based system on the host ship provides the interface to the GESPAC system for operator commands and vessel related parameter display. At present the topside PC is a stand-alone system and does not interface with the survey systems. Planned upgrades will introduce a data link to provide vessel depth and speed data to the survey system, and to allow navigation of the vessel using survey system-generated way-points and differential GPS position. Communication between the the GESPAC and topside computers

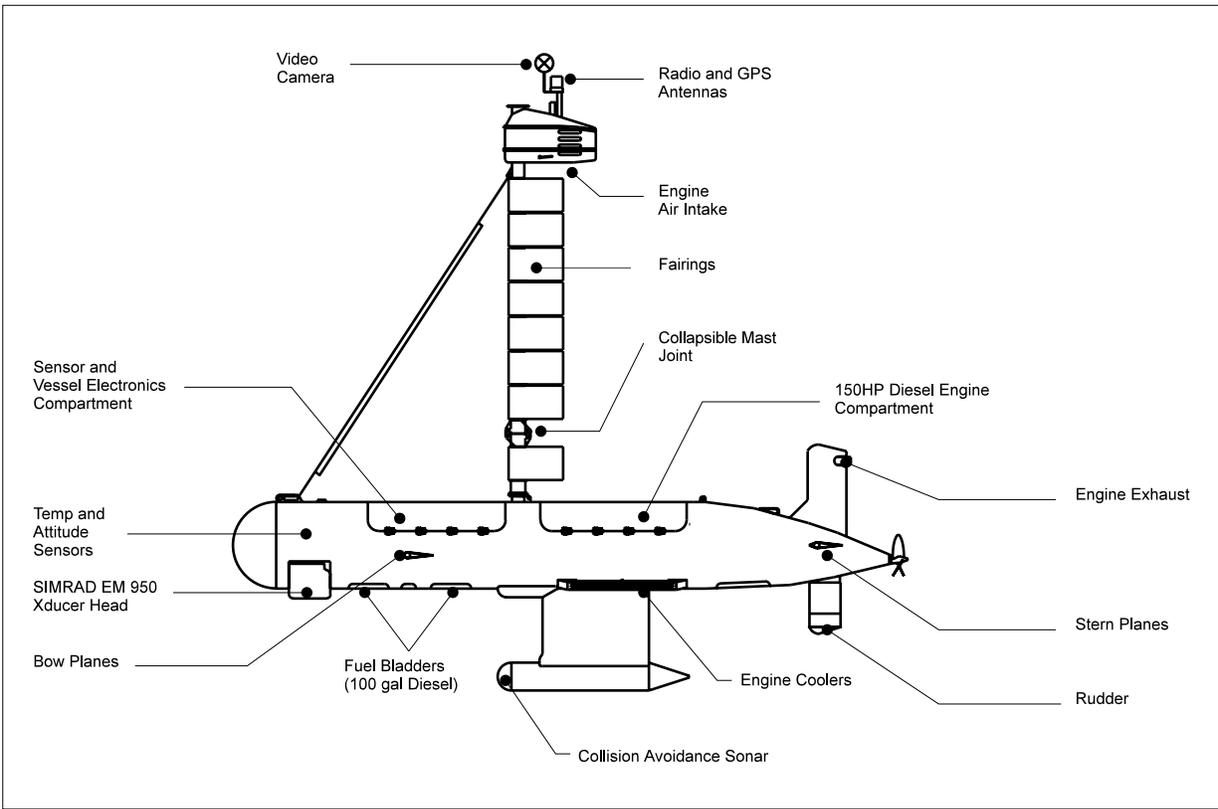


Figure 1: ORCA Vessel Configuration

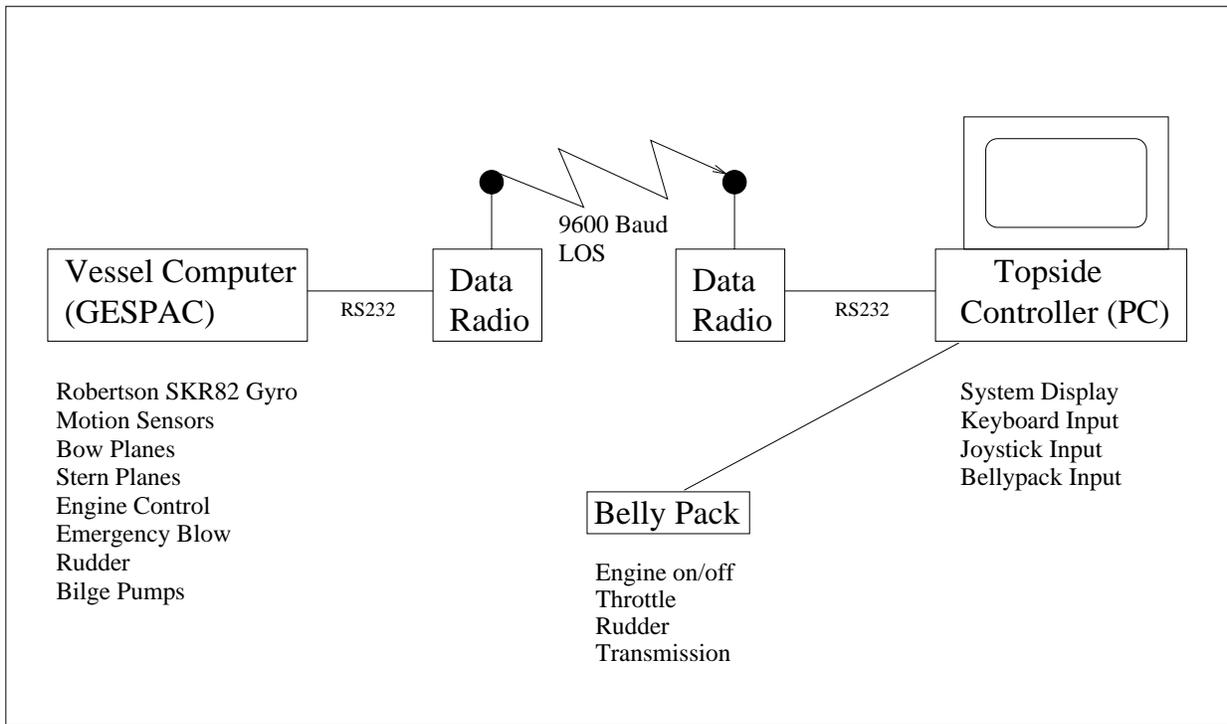


Figure 2: ORCA Vessel Control System

is handled by an FM radio. The radio provides a 9600-baud data link using the 420-MHz band and is manufactured by Data Radio Inc. The present radio has a power output of two watts providing a nominal 4.8km range. This unit will be upgraded to 15 watts with an expected range of 8+ km. An omni-directional antenna is used on both the ORCA and host ship for this system.

The ORCA control system provides several modes of vessel operation: belly pack; heading control; and way-point following, which will be added in the near future. The belly pack uses a portable control unit and umbilical cable allowing the operator to stay within sight of the vessel for close-quarters on-surface maneuvering. It provides rudder control, throttle control, transmission control, and engine start/stop functions. Heading control is the normal mode of operation. In this mode the vessel is operated from the topside PC and the vessel pilot specifies the depth, heading and speed to be maintained by the vessel. In this mode the vessel control system will maintain the specified set points until commanded to do otherwise. All control functions are handled in the vessel computer providing fully autonomous operation. The way-point following control mode allows down-loading of a set of way-points into the vessel computer. The vessel will then autonomously navigate the track designated by the set of way-points. Way-point following has been implemented on the RMOP system [7], developed by the Coastal Systems Station in Panama City FL, but not on the ORCA. The control system includes fail safes for flooding, loss of radio contact, over-depth, and engine or computer malfunction. In the event that any of these occur the vessel surfaces and the engine stops. In the event of a flood in a dry space a compressed air system blows the ballast areas; as a further safeguard a 228-kg drop-weight in the keel is released if the vessel reaches a depth of 12 meters.

On shore ORCA is cradled by a custom trailer, which allows for transportation over short distances and positioning of the vessel at the operation site. Mobilization of the vessel has been performed using a 1 ton pickup truck pulling the trailer for distances of less than 300km. For longer distances the vessel and trailer have been transported using Removable Goose Neck (RGN) tractor-trailer rigs where the total height above the ground (mast collapsed) is just within the 4.1m U.S. federal highway limit. NRL operations to date have launched and recovered ORCA pier side using a crane. CHS operations have been pier side and from a barge. Barge operations entail loading the vessel and a crane onto the barge and using a tug to position the barge. Barge operations allow excursions into waters further from the shore while still providing a significant cost savings over maintaining a dedicated full-size hydrographic survey ship. For deployment from a survey ship, Brooke Ocean Technology Ltd., in Dartmouth Nova Scotia, has developed a DOLPHIN handling system. The system uses an articulated crane and allows launch and recovery of the DOLPHIN vessel from a surface craft, without personnel in the water, in up to sea state 5.

## 4 Bathymetry System

The portion of the sensor systems that are contained in the ORCA vessel are illustrated in Fig. 3. The center of the system is a SUN SPARC20 microcomputer. The SUN handles the tasks of data communication and relay for the various sensors as well as control of the sensors. The SUN does not have its own monitor, and the operator remotely logs into this machine via the topside SUN workstation. Sensing devices can send their data back directly over the ethernet link, or via an interface to the SUN workstation which then relays the data over the ethernet. At present this computer is minimally tasked, allowing for future uses such as data compression and storage, autonomous sensor control, and limited post-processing features.

Communications for sensor system control and data are handled by a high-speed radio link using the Arlan 620. The Arlan is a spread-spectrum radio (902-928 MHz) with a 1-watt amplifier and a HyperAmp-900 5-watt booster. This inexpensive wireless ethernet bridge uses an omni-directional whip antenna on the ORCA and host ship. The basic unit is FCC unlicensed (Part 15) and has a nominal 3.2km range. With the licensed 5 watt booster (DoD only) the radio has been successfully tested at 8km with a 946 Kbit/sec data rate. The bathymetry/imaging system has the highest data rate demand, peaking at 150 Kbit/sec. The ARLAN has proven to be very reliable in this application, with a near instantaneous recovery time after a dropped link and a large data buffer which minimizes or eliminates loss of data.

The Simrad EM950 multibeam bathymetry and acoustic imagery system is the primary sensor on the vessel. It can operate in water depths from 3 to 300 meters below the transducer. It has selectable swath widths which are listed in Table 2. It uses a 95-kHz transducer with 120 dynamically roll stabilized beams and generates collocated bathymetry and acoustic image pixels. Its maximum ping rate is 4 Hz. The individual beams are 3.3 degrees in the fore/aft direction and 1.25 degrees in the athwart ships direction. The system uses a combination of zero phase crossing and peak detection algorithms for location of the bottom in each

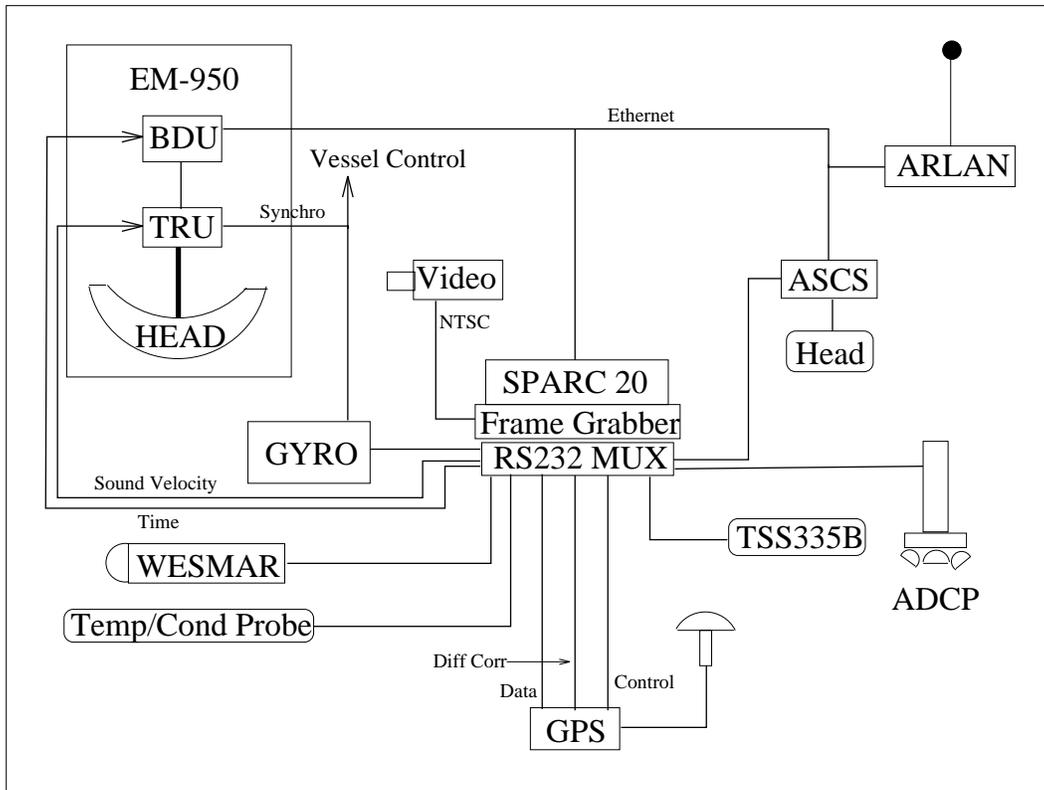


Figure 3: ORCA Vessel Sensor Systems

beam, which provides a depth accuracy corresponding to the larger of 0.3% water depth or 15cm. The system also features 190 degree embankment modes for surveying the side of a channel or along a port or starboard side embankment. With its semi-circular head design, water surface sound velocity does not affect beam steering angle for beams less than  $\pm 60$  degrees. The Bottom Detect Unit (BDU) is connected directly to the ethernet link for data transmission and sensor control from the topside Operator Unit (OPU). The SUN provides time to the BDU and sound velocity profiles to the Transceiver Unit (TRU) via serial interfaces.

Angular Coverage	Horizontal Coverage	Depth Range
150°	7.4xD	3-200m
140°	5.5xD	100-250m
128°	4.1xD	150-300m

Table 2: EM950 Coverage

Numerous ancillary sensor systems are installed to support the Simrad system. A YSI-600 system measures surface water temperature and conductivity at the Simrad transducer. The YSI-600 interfaces to the SUN via a serial line. This data is used to compute the surface sound velocity needed to correct Simrad beam steering at angles greater than 60 degrees. A Robertson SKR82 gyrocompass provides true heading to both the Simrad and the ORCA control computer. The dynamic heading error of this gyro is 0.7 degrees rms x secant(latitude). At 45 degrees latitude this corresponds to a worst case error of one half of the outermost beam's footprint size. The gyro interfaces directly to the Simrad TRU and the vessel control computer via a synchro interface. A serial line is also connected from the gyro to the SUN to provide the topside survey system with instantaneous vessel heading. A TSS-335B vertical reference unit provides heave, pitch and roll data. The heave data is accurate to 5 cm and the roll and pitch data are accurate to  $\pm 0.1$  degree. A Trimble DGPS Survey Module (DSM) receiver is used for vessel position. Its accuracy is 40 meters without

differential corrections, and 0.5 meters with corrections. A GPS differential navigation beacon receiver is used on the host ship to receive the differential correction data, and this data is sent via the ethernet link to the vessel SUN and then via a serial line to the DSM. Data and control is provided by 2 serial lines from the SUN.

The portions of the sensor system that are located on the host ship are illustrated in Fig. 4. On the host ship communication for data and control is handled by an identical Arlan radio and power amplifier. A whip antenna is used on the host ship for this transceiver. The center of the topside systems is an identical SUN SPARC20 workstation, which is the primary control location for the entire system. Data from the various sensor devices is passed either directly over the ARLAN network (Ethernet No. 1) to ethernet capable devices or received by the SUN workstation and provided to the related units through serial links. The data from the vessel BDU is passed directly over the ARLAN network to the Simrad OPU without SUN intervention. A second ethernet link and serial line between the OPU and SUN provide control functions and passing of OPU processed data to the SUN. This second ethernet link also provides a data connection for the workstation running the Hydrographic Multibeam Processing System (HMPS) software. The SUN provides serial port inputs for the host ship GPS receiver, a navigation beacon receiver for GPS differential corrections, and for a host ship heading device (gyro or vector magnetometer). All collected data is logged to the SUN's hard drive, and may be subsequently copied to an 8mm tape drive.

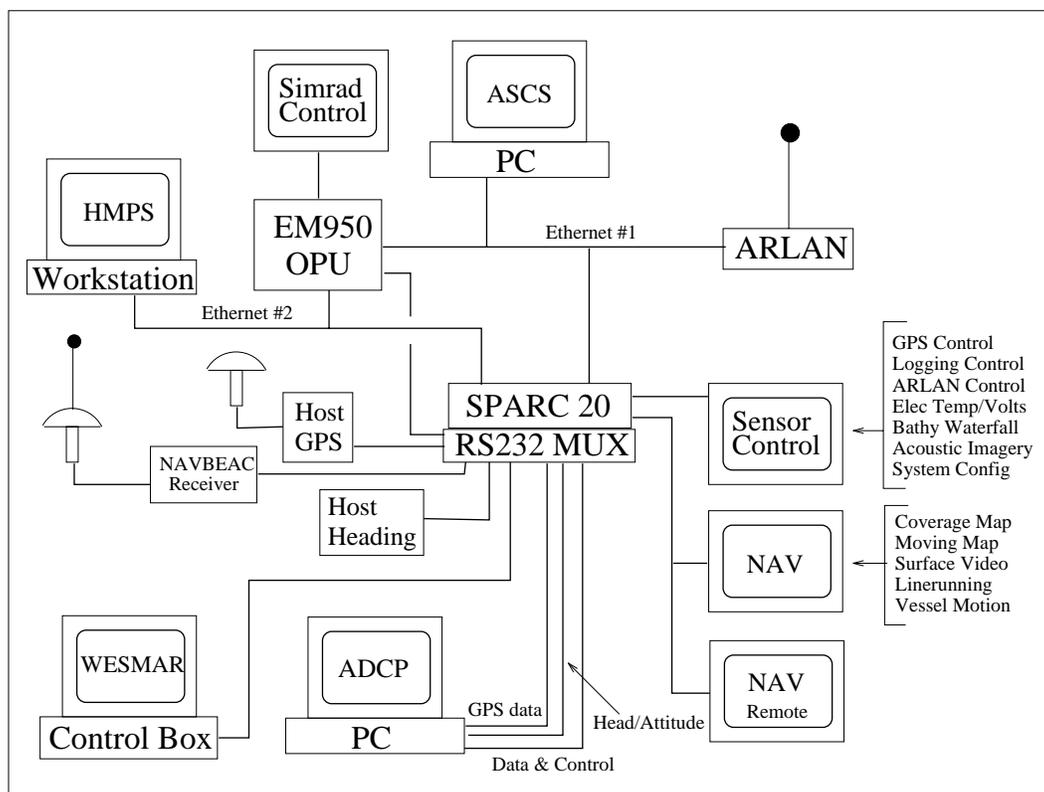


Figure 4: ORCA Topside Sensor Systems

The SUN workstation drives three monitors: one for survey control, and two for navigation display. One navigation display is located locally at the survey control station, and the remote unit is a repeater placed in the vicinity of the ORCA pilot. The survey control monitor is used for system configuration, control and monitoring. A variety of GUI tools are provided for the operator to configure both hardware and software. This monitor is typically used to: display system error messages; display the sonar imagery; monitor the GPS system; display the surface temperature, salinity, and computed sound velocity; monitor ORCA main bus voltage and electronics-bay temperature; control the mast-mounted video camera; monitor the ARLAN radio link; generate and edit survey tracklines and way-points; start/stop Simrad data collection; input sound velocity profile data. Operation of the Simrad EM950 is handled primarily through the OPU.

Track line software on the navigation monitor displays graphically and numerically the desired track

lines and the host ship and ORCA position and heading relative to those lines. This software provides an overhead display of the survey region and a separate indicator for ORCA off-track distance and direction. Collected bathymetry data is superimposed on the overhead display which serves to identify gaps in the coverage. This provides an immediate check of data quality by observing the overlap area between adjacent swaths. A separate window provides a waterfall display of the raw bathymetry data as it is collected. The mast-mounted video display is also on the navigation monitor. A TSS window graphically displays vessel heave, pitch, roll and horizontal acceleration. For maneuvering in restricted areas, an NRL-developed moving map window displays the local area shoreline, navigation aids and the actual position of the ORCA vessel using GPS updates. Other data displayed on the navigation monitor include: depth under the ORCA keel; GPS computed speed and course made good; ORCA gyro heading; lat/long position; x,y,z position for the user selected projection; range and relative bearing of ORCA from the host vessel.

For post processing and final product production both the NRL developed HMPS and C&C Technologies' software were utilized during the February 1995 calibration trials. HMPS provides track line generation, swath data editing, sounding selection, navigation editing, and mosaic generation of surveyed areas. HMPS is the Navy standard multibeam post-processing system that generates selected soundings for delivery to the Defense Mapping Agency (DMA) and ultimate generation of standard nautical charts. The C&C software also provides for data editing and can generate colored relief, 3D perspective and contour charts. The colored relief charts grid the collected data in uniform pixel sizes allowing the presentation of detailed bottom morphology not obtainable with standard numerical depth or contour charts. Their software also provides for editing, mosaicing and production of acoustic images. Using the C&C software and a full size Hewlett-Packard color plotter, same-day charts were produced aboard the host vessel during the February 1995 trials. By digitizing existing charts, C&C can combine shorelines and navigation aids with current survey data. This capability was demonstrated during a May 1995 calibration trial in Gulfport, MS. Likewise, Digital Nautical Charts (DNC) can directly provide this information where coverage is available.

## 5 Bathymetry Calibration Trial

Calibration trials for the EM950 were conducted in February, 1995 off the coast of Pensacola, Florida. Calibration evolutions included standard EM-950, NAVOCEANO and NRL-designed procedures. The goal of the calibration trial was to identify errors such as pitch and roll biases, gyro errors, positional error due to timing delays and overall system accuracy. Three primary sites were utilized for EM950 calibration. Pitch and time-delay tests were conducted in Pensacola Bay which has a 13m deep turning basin. Site 1, at 30° 2'N and 87° 11.5' to 14.0'W, is about 27nm SSE of Pensacola Bay. The site 1 shallow water area (30-35m) was used to perform roll and gyro calibrations. A star pattern was also run in this area by crossing over a point in eight different directions to determine the effects of prevailing seas and heading on vessel attitude motion. Site 2, at 29° 28' to 29° 30'N and 87° 24'W to 87° 26'W, was previously surveyed in 1990 by the U.S. National Oceanic and Atmospheric Administration (NOAA) ship *Whiting* with the Hydrochart II 36kHz multibeam system. Site 2 is 50nm south of Pensacola bay and was used as a deep-water (90-300m) calibration site for the EM950. Site 2 was subsequently surveyed with the NAVOCEANO vessel USNS *Pathfinder* on May 3, 1995 using the 12-kHz Simrad EM-121A multibeam system. At site 2, the same tracklines were run by all three vessels, with two additional cross-tracks run by the ORCA and *Pathfinder*.

Site 2 was used to evaluate bathymetry results from ORCA's EM950 with the NOAA Hydrochart II and the NAVOCEANO EM-121A data, and also to evaluate accuracy of the EM950 outer beams. The bathymetry comparisons are based on 12, 36 and 95 kHz systems, so uncertainty about sonar bottom penetration at these three frequencies is likely to affect the computed accuracies. Table 3 summarizes the results of the comparisons between the three systems. In Table 3 OR-PF refers to ORCA less *Pathfinder*, OR-WH to ORCA less *Whiting*, and PF-WH to *Pathfinder* less *Whiting*. For these calculations data was processed and resampled to a 0.01' grid. Comparisons were based only on real data points at each grid interval; interpolated points were not utilized. It is apparent from the percentage of negative residuals in Table 3 that the *Pathfinder* and *Whiting* sounded deeper than the ORCA and the *Whiting* sounded deeper than the *Pathfinder*. It's expected that the 12 and 36 kHz systems would sound deeper than the 95 kHz system. However, it is uncertain why the *Pathfinder* sounded shallower than the *Whiting*. The *Pathfinder*'s EM-121 system was still undergoing acceptance tests at the time of the survey, and some problems were known to exist with timing offsets.

Figure 5 shows the 25m contour lines for the three platforms. The ORCA 95kHz system consistently

Residual	OR-PF	OR-WH	PF-WH
RMS	3.17	8.13	5.18
Mean res.	-3.11	-8.04	-5.05
Std dev. $\sigma$	0.59	1.16	1.19
$\sigma$ (% depth)	0.28	0.55	0.55
% negative	100.00	100.00	99.97
minimum	-6.83	-13.9	-12.56
maximum	0.00	-0.07	0.01

Table 3: Depth Residuals Between Platforms in meters

sounded about 3m shoaler than the *Pathfinder* 12kHz system, but agreed closely when this 3m bias was removed. Some of this 3m depth bias may have been caused by greater bottom penetration of the 12kHz sonar into the predominately mud seafloor. In comparison with the *Whiting*, the ORCA data was 6-7m shoaler in the shallow regions (90m depth) and about 2-3m shoaler in the deeper regions (300m depth). The reason for this apparent difference in bottom slope is uncertain. Two factors may contribute to these differences; sound velocity data was obtained by the *Whiting* on the first day of the survey using a Conductivity/Temperature/Depth (CTD) cast. On the following days, expendable bathythermograph (XBT) sound profile drops were made and compared to the original CTD cast. According to the NOAA descriptive report for this survey [8], all comparisons were within the tolerances specified in the NOAA Standing Bathymetric Mapping Instructions. However, an error in the original CTD cast could introduce errors in the measured depths. A second possible explanation for the difference in apparent bottom slope involves vessel positioning. The *Whiting* survey was conducted in 1990 using STARFIX satellite navigation with daily DGPS comparisons, while the ORCA and *Pathfinder* surveys utilized DGPS at all times. Since the depths in site 2 range from about 75m at the northern edge to about 300m at the southern edge, a small error in north/south positioning could induce a significant depth error along this relatively steep slope. A contributing factor may also be mud slump during the 5 year period since the *Whiting* survey.

An analysis of overlapping beams for the EM950 was done for the site 2 data. The goal was to compare the center beams of tracks with the outer beams of adjacent tracks that overlapped the same area. Since the track spacing was not designed for the EM950 geometry there was not exact correspondence between center and outer beams. An allowance was made to compare any outer beams that were within 15m of the adjacent track's center beam. The 15m allowance, with a 3% slope, would allow differences within 0.5m. The mean difference was computed between line 4 outer beams and line 5 center beams, where the best overlap occurred. The mean difference was 0.35m, with a standard deviation of 0.43m. This is well within the International Hydrographic Organization (IHO) standard of 1% of true depth in this area (175-202m). For these observations, the 90% confidence interval is  $0.35 \pm 0.7$ m. The same test applied to all lines, spanning 133 to 275m depths, yielded an average difference of -0.66m, with a standard deviation of 0.97m between the outer and center beams of adjacent tracks. There is at least a 90% probability that the true depth is within 1.6m of the estimated depth, e.g. within IHO specifications. The port and starboard beams were seen to vary in accuracy when compared to overlapping center beams. The port beams had a mean bias of -1.37m, which was significantly larger than the mean bias of 0.09m for the starboard beams. The observed difference in port and starboard bias could be attributed to roll bias.

The EM950 bathymetry showed good repeatability as measured from 168 observations over the area at the center of the star pattern at site 1. The mean depth measured in this area is 38.04m with a 0.15m standard deviation. The 90% confidence interval for the observed mean is  $\pm 0.24$ m which is well within the IHO standard requirement of  $\pm 0.38$ m. A line was run at site 1 to compare the data collected using different EM950 modes: 75°, 128°, 140°, 150° equidistant beam spacing (EDB) and 150° equiangular beam spacing (EAB). The data collected was gridded at a 0.003' spacing. Table 4 shows the results of comparisons between the 150° EDB spacing and the other operating modes. The table indicates acceptable concurrence between the different system modes.

The star-pattern data collected at site 1 also provided insight into the effects of sea-state on vehicle motion at different headings. It was observed that the ORCA pitches at a larger amplitude when running with the seas, as opposed to running into the seas, where it is much more stable. This is likely to be a

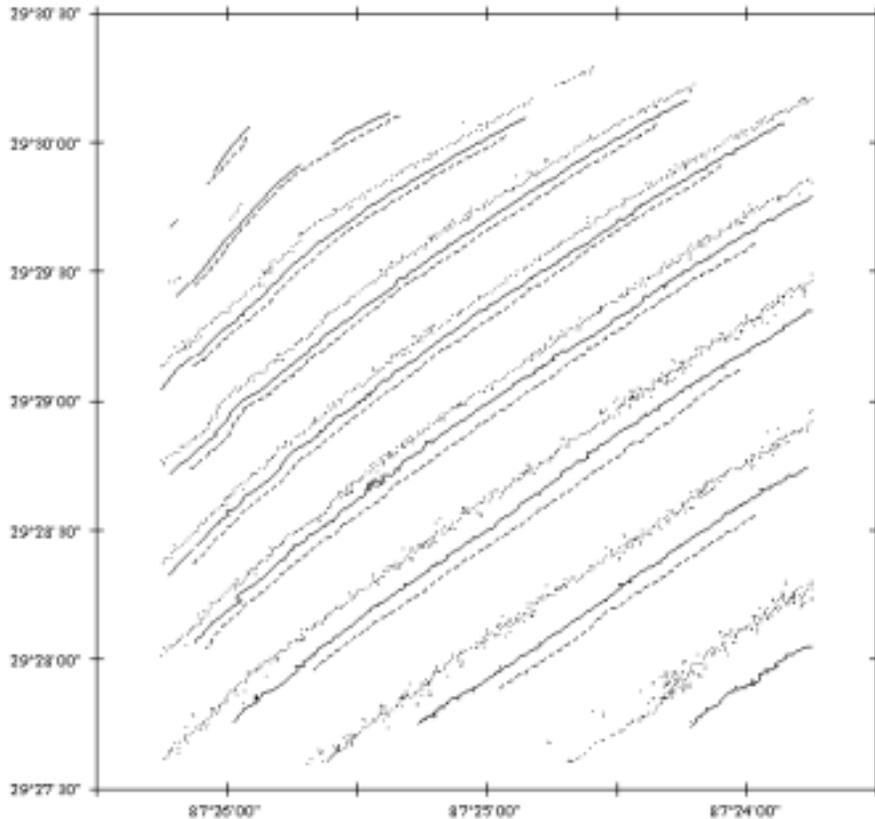


Figure 5: Site 2 survey area near Pensacola, FL, showing 25m contour lines for Whiting (dotted), Pathfinder (solid) and ORCA (dashed).

consequence of the relative period of the waves as seen by ORCA. For short periods the variations in depth due to the waves will be filtered and ignored. When traveling with the seas the relative period is much longer, and the ORCA's depth control system will be more likely to attempt to follow the waves. These results are consistent with previous studies [3], and indicate that ORCA should not be run with the seas for surveys executed during high sea-states. During the data collection period the seas were running approximately  $260^\circ$  with a 4-5kt wind. The amplitude of the ORCA pitch was seen to be significantly larger for the  $270^\circ$  steered heading than for other headings.

In Pensacola Bay lines were run at different speeds over the edge of the turning basin to determine pitch and time-delay errors. During this evolution it was observed that vessel depth changed as a function of its speed, although the depth readout remained constant. This error rendered the data unusable since precise vessel depth was not known. It is believed that the problem resulted from relocation of the depth sensor ports on the vessel. Attempts have been made to correct this problem and the system will be retested during the next sea trial. In the event this problem cannot be completely resolved within the capability of the vessel's control system, vessel depth can be visually observed by marking the mast, and a table will be constructed for speed vs. depth.

Roll biases were determined by analyzing data from both sites 1 and 2 using graphical and numerical methods being developed at NRL. The graphical method involved overlaying cross-track depth profiles for portions of reciprocal lines over a flat area and visually determining the offset. Since this offset is small, several roll bias estimates were used to iteratively correct the data and a 0.15 degree roll bias to starboard was found to empirically provide the best solution. Using the numerical method a roll bias estimate of 0.07

Residual	150° EAB	140°	128°	75°
RMS	0.19	0.17	0.15	0.11
Mean res.	-0.04	0.04	0.01	-0.06
Std dev. $\sigma$	0.19	0.16	0.12	0.10
$\sigma$ (% depth)	0.50	0.43	0.31	0.26
% negative	60.74	36.97	17.96	73.53
minimum	-1.06	-1.31	-0.31	-0.53
maximum	1.15	2.15	2.89	0.48

Table 4: Depth Residuals Relative to 150° EDB in meters

degrees to starboard was obtained, agreeing reasonably well with the graphical method. This bias is easily corrected with the Simrad software.

The gyro data for one of the site 1 lines is plotted versus time in Figure 6. The data shows an overall sinusoidal side-to-side motion with a peak magnitude of about 2 degrees, which is expected for an actively controlled vessel. Of concern however, is the anomalous flat spots observed for up to 3 second intervals. The data shown was generated by the EM950 which digitizes the gyro’s synchro signal at a 0.1 degree resolution. While this apparent error did not significantly affect the computed bathymetry this anomaly will be investigated during the next sea trial by comparing the gyro’s digitized output with that of the EM950. A possible cause of the flat spots could be a ‘stalling’ of the vessel heading at the sinusoidal peaks. As the vessel sways it may hang for several seconds at its maximum travel until the rudder action effects a return. However, this does not adequately explain the mid-cycle flat spots which are seen to be typically of shorter duration.

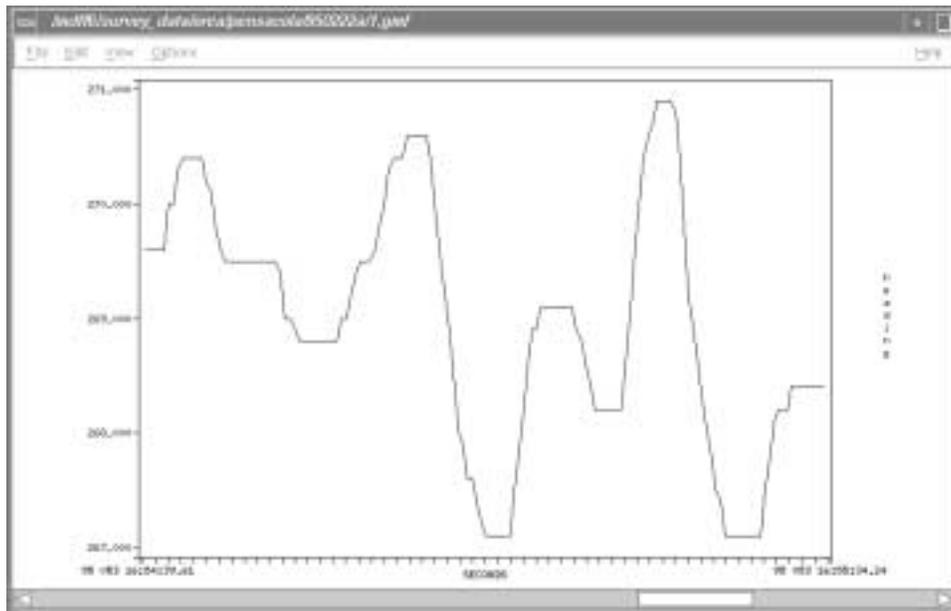


Figure 6: Gyro Heading Versus Time

## 6 Additional Sensor Systems

For enhanced navigation safety, two additional systems have been added for obstacle avoidance. A mast-mounted video camera provides a real-time forward view above the surface of the water. The camera used is a Simrad OE 1359 CCD with a 90-degree view angle. This camera interfaces to the ORCA SUN workstation through a frame grabber and the video images are sent over the network using the “nv” network video tool.

nv was developed for multicast applications, and provides data compression, variable size images, data rate control, and image contrast and brightness control. A 1-2 frame per second update rate has proven sufficient for the application and requires a data stream of about 70 kbits/sec. The image from the camera is displayed on the topside SUN's navigation monitors. A planned upgrade of this system is the acquisition of a zoom and near-infrared capable camera.

A modified Wesmar model TCS600E scanning sonar has been mounted on the forward end of the keel to provide a forward view below the surface. This is a 60-kHz sonar with a mechanically scanned planar array. The sonar has a 15-degree beam and a maximum range of 1600 meters. The unit's control system allows manipulation of both lateral and vertical scanning directions. Data communications for the system are achieved by a serial link from the head of the sonar to the vessel SUN, and a serial link from the topside SUN provides to the sonar control unit. The control unit has its own display which will be positioned in the vicinity of the ORCA pilot. Ultimately it is desired to integrate the control and display functions of the unit into the topside SUN in order to eliminate the additional control box and monitor. The displays from the camera and sonar systems will provide the vessel operator on the host ship a complete 'look ahead' picture from the ORCA's perspective. Future plans for the obstacle avoidance system include the implementation of image-based autonomous obstacle detection using data from the camera and sonar.

Two oceanographic sensors are presently being integrated into the NRL vessel, the NRL developed Acoustic Sediment Classification System (ASCS) and an RDI 150-kHz Acoustic Doppler Current Profiler (ADCP). The ASCS uses a 30-kHz narrow-band pulse and provides a vertical profile of the seafloor sediments [9]. The processing algorithms generate acoustic impedance and subsequently classify the seafloor composition. The sonar head for the ASCS is mounted on the forward end of the keel and is connected to the transmitter unit in the electronics compartment. The ASCS transmitter unit connects directly to the ARLAN ethernet link. An ethernet capable PC is used on the host vessel to: send commands; and to receive, post-process and display the data.

The ADCP provides current profiles and bottom tracking in water depths of over 300 meters. The unit is self contained and has been mounted along the aft end of the keel. A single serial link is used between the ADCP and the vessel SUN for control and data communications. On the host ship the SUN provides a serial link to the PC running the RDI Transect software. The Transect software performs post-processing and display of the collected data. Two additional serial links are provided between the topside SUN and the ADCP's PC. One provides GPS time, position, heading and velocity data, and the other provides ORCA gyro heading and TSS pitch and roll data.

A desired upgrade to the survey system is the integration of a strap-down inertial navigation system incorporating GPS, inertial and ADCP bottom tracking. Strap-down inertial systems such as the POS-MV [10] have already been demonstrated with Simrad bathymetry systems and allow survey data to be collected during vessel maneuvers. The inability to survey during turns is a common drawback of contemporary survey vessels. Typically the vessel must maintain a constant heading for several minutes to allow the inertial systems to settle out after executing a turn. The POS-MV utilizes a ring laser gyro vertical reference unit and DGPS coupled through a Kalman filter. Incorporating the bottom tracking information from an ADCP will provide excellent short-baseline navigation accuracies. ADCP's have reported bottom tracking accuracies of .01% of distance traveled and can provide accurate positioning in areas where DGPS is not available. A related advancement is the the integration of a multi-antenna GPS heading system. Off-the-shelf systems can provide heading accuracies of 0.1 degrees with only a 1-meter antenna separation. These systems are more accurate and require less power and space than a gyrocompass.

## 7 Autonomous Survey Control

As seen in Figures 2 and 4, a large number of computer monitors are required to operate the system. The vessel pilot has three monitors, the vessel control monitor, the navigation monitor repeater, and the Wesmar monitor. The survey control station has the sensor control monitor, the primary navigation monitor, the Simrad control monitor, and a monitor for operating the HMPS system. The ASCS and ADCP systems each add their own monitor. The system as shown requires five trained operators to function. Figure 7 breaks the system down into functional elements and indicates which functions are presently handled by machines and which are handled by humans. This figure clearly displays that the operation of the survey system as a whole is very operator intensive, even with state-of-the-art sensor technology.

The vessel itself is an autonomous system, able to maneuver and maintain a dictated track. But at its

current stage of development it is blind and deaf, requiring a human operator to perform the functions of obstacle recognition and obstacle avoidance. While automation of these functions is not a trivial task, it is an area of active research in the AUV and robotics communities and significant progress has been made. An incremental improvement in the system would be the automated recognition of potential obstacles using the video and acoustic images received from the sensors. The system would alert the vessel pilot of possible obstacles and leave the more difficult task of evasive maneuvering to the operator. A fully capable evasive maneuvering function would be difficult to automate with the ORCA vessel given the limitations of its sensory input; a surface radar would be required to provide the relative motion information needed to avoid other moving surface craft.

Automating sophisticated sensor systems may prove to be the most difficult aspect of converting this to a fully autonomous system. Generally each system requires an expert-in-the-loop observing system performance on the displays and modifying system or survey parameters through keyboard or control panel input. As an example, consider the execution of a bathymetry survey. A standard survey involves driving several parallel paths with a desired overlap in the coverage areas for data verification. To a great extent a parameter as seemingly trivial as path spacing cannot be pre-determined. The bathymetry system bottom coverage is affected by water depth, bottom slope, ambient noise and bottom reflectivity and these variables are not typically known a priori. Additionally, the direction of the waves may dictate the tracks chosen to minimize platform motion. The instrument operator must periodically inspect displays that give clues to data quality and adjust system parameters, trackline spacing and trackline orientation based on empirical observation and experience.

Full automation of the sensor systems will involve the development of expert systems to monitor the operation of each. Many of the systems already have some rudimentary capability for remote operational control from an external computer that could be utilized by a rule-based system. The majority of real-time status checking performed by the operator is done using displays of processed data, and intelligent signal processing algorithms will have to be developed to mimic the analysis performed by the operator. Many of the systems are PC based, prohibiting easy incorporation of supervisory control software. Consequently, the vendor software would have to be ported to a multi-tasking platform - a fairly simple evolution, but time consuming and costly. All of these developments would necessarily require a close liaison with the instrument manufacturer as substantial modification of the existing systems would be needed. Incorporation of these sensors into a fully autonomous submersible will require not only the advancements discussed, but also the integration of a significant amount of additional computational power into the vessel.

## 8 Project Status

Work commenced on the ORCA project in February 1994. The two original vessels have undergone complete overhauls, and the forward halves of the vessels have been completely replaced to increase fuel capacity and enlarge the dry electronics compartment. The first vessel underwent a shakedown cruise in August 1994, and the second vessel in December 1994. The complete sensor system was installed in the first vessel and tested out of Gulfport, Mississippi in January 1995. It underwent a calibration trial operating out of the Pensacola, Florida Naval Air Station in February 1995. During the calibration trial the Simrad system was tested to its full depth capability of 300 meters. This operation included night time and foul weather conditions with launch and recovery performed pier side using a 30-ton crane. The operation also had a 21-hour duration trip to a survey site 50 miles out from the sea buoy. Charts were generated on site using data collected by the multibeam system of the various offshore survey areas and of the Pensacola Bay channel. Also during this mission the moving map display was demonstrated using a portable PC-based system. The software has since been modified to run on the ORCA's topside Sparc20 computer.

During the remainder of this year, NRL plans on field testing the RD Instruments' 150-kHz ADCP and the NRL-developed ASCS on the first vessel. The second vessel sensor system and the subsurface collision avoidance system are installed and underwent sensor pretrials and debugging in early May. Simple operations and maneuvering of two ORCA's from a single host was also demonstrated during the May trial. By July 1995, a Simrad EM1000 sonar will be installed on ORCA #2, extending survey depth capability to 1000 meters. Calibration trials for this vessel are scheduled for July and September 1995 out of Pensacola, Florida. The July operation will include a demonstration survey using both ORCA vessels simultaneously collecting and transmitting hydrographic data to the same host ship. During this operation generation of same-day charts including navigation aids, shorelines, and other standard chart features will be demonstrated. Upon



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