SECTION 12

John Van Leer

Small Catamaran Research Vessels

Commercial catamaran vessels have been steadily evolving over the last 35 to 40 years, with the guidance and the continuing evolution of Det Norske Veritas rules. Hundreds of commercial catamarans have been built, and continue to be built world wide under these rules primarily in Norway, France and Australia progressing through several generations of ever lighter, ever stronger, ever faster catamarans. Down through the centuries, catamaran users have realized that catamarans make poor freighters. As a result, recent design directions have stressed either high speed, semi- planing, passenger ferries, which are refueled daily, or displacement motor/sailing passenger vessels for longer duration cruising. Both of these applications stress enhanced sea keeping over cargo hauling with two distinctly different approaches. The UNOLS fleet includes about two dozen single hulled ships well suited to carrying substantial freight. Thus we will not discuss the duplication of this capability in a catamaran hull here.

In the first part of this chapter, a brief discussion of catamaran history is presented. Secondly, a general discussion of the most significant characteristics and tradeoffs in catamaran design parameters is set forth. Thirdly, a design for a catamaran research vessel optimized around a center well is presented to illustrate one set of logically consistent choices. Lastly, this conceptual catamaran is applied to supporting four innovative motion isolation systems well suited to remote sensing and direct sensing observations. These motion isolation systems and a number of applications give a preview of how the author thinks a 21st century robotic ship might look and work.

Early Background -The Polynesian Period

The catamaran vessels of today are the direct descendants of the highly evolved Polynesian sailing vessels. These vessels were used to colonize every habitable island in the vast area of the tropical and subtropical Pacific and Indian oceans, referred to as Oceania (see Canoes of Oceania by Hadden & Hornell 1936, 1937 & 1938). The colonization of this region started about three thousand year ago from Asia and was essentially completed in Hawaii about one thousand years ago. In 1774 Capt. James Cook had the lines taken off a 108' long catamaran (Brown 1938). Catamarans may seem new and exotic to many in the western oceanographic community, but they are traditional in the other half of the world.

Western Catamaran Developments During the last 350 years

Early western attempts at building Catamarans include Sir William Petty's Double Bottom in 1662 (Brown 1938). She beat all comers in a race in Dublin establishing the speed potential of catamarans in the Western Hemisphere. Most early steamboats including Fulton's 1812 ferry boat Jersey were catamarans where the paddle wheel was protected between the hulls (Brown 1938). The connecting structure between the hulls was used for navigation and became known as "the bridge". The first steam powered war ship, the 156' Demologos, was a double-hulled steamer built for the war of 1812. Steam catamarans remained popular in America, Europe, and

Australia until the screw propeller replaced the paddle wheel around the time of the American Civil War. In all, Brown lists about 130 large western catamarans before 1938.

Western Perception of Catamarans Shaped by Yachting

The brilliant naval architect Nathaniel Green Herreshoff designed at least 7 catamarans including the Amaryllis which beat all comers at the New York Yacht Club's Centennial Regatta in 1876. This victory lead to catamarans being classified as freaks by the yachting establishment and thus excluded from "proper yacht" racing for about a century.

Since Dennis Connors successfully defended the America's Cup in a catamaran, against a mono-hull twice her size, catamarans have become more accepted in the U.S.A. In last year's Miami in Water Sail Boat Show, multi-hull cruising vessels outnumbered conventional cruising vessels for the first time. Similar growth is beginning to be seen in powered catamaran yachts. This explosive growth has also led to a number of poorly designed vessels by inexperienced multi-hull designers getting in on the trend. Thus a considerable shakedown period will be needed.

In the United States only limited commercial catamaran use has occurred during the last decade. The commercial trends overseas suggest that the time for building a catamaran research vessel optimized to take advantage of the catamaran's positive attributes has arrived. However, past mistakes, like the heavy designs of the R/V Ridgely Warfield (106' LOA and 162 L T displacement) and R/V Hayes 35 years ago, have made the oceanographic community understandably wary of catamaran research vessels.

Western interest, materials and technologies have expanded the possible catamaran design envelope. The most significant progress has followed the evolution of modern metals, resins, and fibers, post World War II. The experience of most marine scientists has been limited to the capabilities of mono-hulled vessels designed in the western cargo/fishing traditions with very limited experience with multihulled vessels. This accounts for the above mistakes by past ship design committees. (see VanLeer 1982). Catamaran research vessels are potentially among the most useful but frequently misapplied vessels for research at sea.

Catamaran Research Vessels

The design of any vessel is a series of compromises which trade off one property for another. Catamarans are particularly appropriate in the size range from 45 to 170 feet, where they offer many of the advantages o f considerably longer conventional vessels in a shorter, wider, shallower draft, fuel efficient package. The R/V Sunbird (46 feet LOA) operated out of Lizard Island, Australia, has been an effective, comfortable, rugged vessel for use on the Great Barrier Reef and Coral Sea. In order to gain the greatest research benefit from the catamaran hull form, we will first examine those applications where modern catamarans have enjoyed the greatest commercial success.

High-speed passenger ferry and tourist catamarans have become dominant in many overseas commercial markets. These applications take advantage of shallow draft, large deck areas, high propulsion efficiencies, excellent seakeeping and maneuverability afforded by slender, widely separated hulls and propulsion. These applications clearly stress excellent seakeeping rather than freight hauling applications. Most of the passenger ferries have relatively short ranges with fuel readily available on a daily basis. This reduces fuel loading and permits cruising speeds of 15 to
50 knots with semi-planing or wave piercing hull forms. High speeds doppler shift the encounter frequency of surface gravity waves above natural pitching resonance dramatically smoothing out the ride.

However, for long range oceanographic vessels, fuel loads increase so that slender displacement hull shapes are favored and water plane area must be reduced to improve seakeeping at low speed. Oceanographic vessels spend a lot of time on station near zero speed and thus can't benefit from the above doppler shift. The 73 foot D MB pearl fishing catamaran (Crowther Design #73) stays out for two weeks and spends most of its working life at anchor on station, so it's design is based upon a slender displacement hull form evolved for sailing. This vessel carries 13 long tons (LT) of pearl shells and seawater with a range of 1350 nautical miles at 9 to 10 knots and is described in Crowther (1982). Designing and using modern catamarans is lot like designing and using aircraft where strength/weight considerations are crucial. Weight control is essential for good and safe performance offshore. Blind application of monohull design ideas has lead to the creation of a number of needlessly heavy (and thus expensive) catamarans with poor seakeeping. Fuel load takes the place o f science cargo as the primary weight to be hauled, which in turn requires larger engines to achieve the design speed and range, which requires more fuel and so on. The design spiral then diverges from well-proven wholesome, catamaran design practice. The resulting vessel has a semi- planing hull but insufficient power to "get over the hump" and plane. See Harris (1998) and Band Lewis (1999).

Multihulls or Fundamentally Different in Stability from Monohulls

In monohull design, the form of the hull is essential in determining the stability of the vessel so that there are strong limits on the fineness ratio (hull length/hull beam at the waterline). Destroyers, for example, are near the upper fineness ratio limit in order to gain a greater hull speed and fuel economy, but suffer poor roll stability and are thus notoriously uncomfortable in rough conditions. Twin hulled vessels gain their essential stability by two widely spaced hulls and to a lesser degree by the shape of the individual hulls. The most essential decisions the catamaran designer must make are the fineness ratio of the individual hulls and the overall weight (including all permanent science equipment, science cargo, fuel, machinery, finishings, fire protection etc.).

Many commercial catamaran hulls have a fineness ratio of 20 without significant stability problems. In fact, some SW A TH vessels (.Small WAterplane Twin Hulled vessels) have fineness ratios well beyond 20, trading almost all of the high inherent catamaran stability in favor of enhanced seakeeping in moderate sea states. However, SWATH vessels are deeply rooted in the water and might become dangerous in extremely large, breaking seas if the vessel loses power and becomes aligned with the wave crests. A large breaking sea striking such a disabled SW A TH vessel a'beam could overcome the vessels modest stability. By contrast, light displacement, shallow draft catamarans will slide sideways rather than capsize under the same conditions as clearly demonstrated in Crowther catamaran Model Testing films simulating hurricane conditions.

At the other extreme, some heavy displacement catamarans have been built with a fineness ratio of less than 7 to gain greater capacity to carry cargo. While such a vessel is somewhat dryer on deck, this choice results in a very rough ride due to excessive stability giving rise to unpleasant snap rolling and pitching motions. This was demonstrated by Harris (1998) and (1999) Band Levis model test series with accelerations approaching one g in 4 to 8' head seas measured at the bow. Hull fineness ratios near 12 seem to offer the best compromise, retaining both good seakeeping and reasonable cargo carrying capabilities as demonstrated by the successful operation of DMB (Crowther 1983). A semi-circular, immersed hull form is frequently used to reduce wetted surface and its attendant skin friction losses in slender displacement hulls. Such a hull form also provides reasonably shallow draft with modest skegs (with grounding shoes as seen in figure 3) for extreme shallow water operation and reasonable puncture protection.

Catamarans Have Large Deck Areas Which Invite Overloading

Because the area between the hulls can be used for science, unusually large deck areas and laboratory spaces are potentially available. There is a natural temptation to fill the entire area between the hulls with solid decking. However, weight in the ends of the vessel increases its moment of inertia about the pitch axis and increases the tendency of the vessel to develop a violent pitching motion as above. If the vessel hulls are nearly symmetrical about the pitch axis, as in the R/V Hayes, the tendency toward large amplitude synchronous pitching is aggravated. Therefore, the R/V Hayes was retrofitted with an immersed foil between the hulls well forward of the pitch axis to damp this tendency. Large areas of solid foredecks not only increase the pitching and slamming tendencies, but also act as scoops for boarding head seas in heavy weather, and thus should be avoided for safety reasons (see Band Lavis 1999). Excessive superstructure height can have much the same effect. Large weights like engines and tankage should be carried as near the pitch axis as convenient, and low in the hulls. Amidships weight in the hulls tends to lengthen the roll period which is usually a benefit. State rooms are often placed in the hulls above the tankage to make more space on the working deck for labs, open decks, center wells and common areas like the galley/mess.

Under Wing Clearance and Space Between the Hulls

Wave motion on the sea surface between the hulls contains not only natural surface gravity waves, but also the wake emerging from the bow of each individual hull. Consequently, the space between the hulls should be adequate for wave passage without colliding the underside of the connecting structure between the hulls (slamming). The intersecting bow wave patterns produce humps and valleys in the sea surface between the hulls which move aft as speed increases, leading to significant variations in the propulsion power as a function of increasing speed from the expected square law dependence. So, for a given hull shape and spacing, there may be preferred operation speed ranges where enhanced efficiency is possible. Bows which extend beyond the superstructure by about 30% of the ship's length, allow the vessel to rise to an oncoming sea before it encounters the wing structure (see Band Lavis, 1999). Bulbous bows have been used by Crowther and others to suppress bow waves and damp pitching motions.

If each hull is symmetrical about its center line, the space between the hulls becomes progressively narrower aft of the bow, creating a convergent channel which will amplify waves approaching from the bow. This undesirable effect becomes more pronounced as the hull fineness ratio is reduced. In some extreme cases, the space between the hulls is less than each hull beam measured at the waterline resulting in more than doubling of oncoming wave amplitudes. Unless such a vessel is slowed dramatically in head seas, it will slam frequently (see Band Lavis 1999). Most offshore catamarans employ netting between the hulls forward of the main connecting structure so that breaking wave crests can pass through without overloading and depressing the bow from above or slamming from below.

Adequate underwing clearance will reduce the chance of slamming. Five percent of the catamaran's length is considered minimum clearance in the fully loaded condition with full fuel. Overloading will not only increase vessel stresses, but reduce the underwing clearance, and reduce propulsion efficiencies (see Band Lavis 1999). In a monohull, maximum load is frequently limited by reduced stability. However, a catamaran becomes more stable with load. Clearly, common sense is required when loading a catamaran, by conforming to the designed full load specification (see Band Lavis 1999). With today's easy shipment of containerized cargo, it is no longer necessary to carry everything which will be used on a multi-legged cruise for the duration of the cruise. In coastal regions with reasonable fuel availability, it is likewise not required to carry fuel for an entire multi-legged cruise.

The Center Well Option - A Primary Reason to Choose a Catamaran

It is possible to arrange a catamaran to permit a true center well at the pitch and roll center of the vessel without cutting into the ship's bottom. This location is at the point of minimum motion and acceleration and is useful for drilling, coring and general purpose wire lowered instrumentation. The catamaran R/V Lu Lu operated by W.H.O.I. for many years had a makeshift hull design based upon two extraordinarily heavy pontoons available from Navy surplus, but it did have a fully functional center well with an elevator to launch the deep submersible, Alvin. The author had the pleasure of using this center well to launch and recover instrumentation in rough conditions while Alvin was on a dive. The convenience and safety of the center well was so great it lead the author to wonder why all catamaran research vessels didn't launch their gear through true center wells. The R/V Hayes deploys an extremely large and complex acoustic array through its ample center well, with excellent results. Clearly, there is a compelling reason why all deep sea drilling vessels have center wells. In a catamaran with widely spaced hulls, a large center well is more practical because it avoids problems with surge common within hull piercing center wells, and the added parasitic drag of a large opening in the bottom of the hull.

To test the dynamic response of wire lowered gear in center wells, the author built a center well in his 36' catamaran, straddled by a tripod which had a turning block located near the pitch and roll center of the vessel. This general arrangement, included a self breaking, air driven winch, permitted the safe launching/recovery of 660 lb. anchors from this 4,000 pound vessel in 4 to 6 foot seas. The motion of the anchor was s o gentle that restraining lines were scarcely needed. This is a stark contrast to the danger of handling such a weight over the side or stern of a conventional vessel of similar size in 4 to 6 foot seas.

An Optimized Catamaran Research Vessel Designed by Crowther

Until Hubble, astronomers had to settle for blurred images seen through a turbulent attenuating atmosphere. Oceanographers and meteorologists have begun to image the ocean and the atmosphere from ships through a variety of sensor systems. They too have had to cope with turbulent attenuating media, but the motion of their observing platform, the ship, has had far greater noise producing effects than typical satellite or aircraft platforms. Described here is a catamaran ship designed by Crowther Multihulls to accommodate a set of four related motion reduction techniques for a frontal attack on ship motion induced errors, stresses and hazards.

This vessel relies on four distinct techniques to reduce motion. The large scale of these devices also makes them useful for direct sensing of the ocean, atmosphere, and bottom. Manipulators of appropriate size are suggested to bring the maximum capabilities of the ship to bear on projects, while isolating undesirable effects of ship motion. This will enhance the quality of observations, while introducing a whole new level of safety as scientific personnel are removed from "hero platforms" and replaced by robotic devices. Simultaneous stabilized measurements can be made above and below the sea surface from a common motion stabilized pendulum.

These devices are: (1) A Motion Compensated Pendulum (MCP) deployed through the center well at the pitch and roll center of the vessel (Figure 2). (2) A motion compensated A-Frame Mast (Figure 1). (3) A system of 4 spuds for stable shallow water anchoring as (Figure 2 and 3). (4) A Motion Control System with four inboard control fins to reduce pitching and heaving motions about 50% while underway. The four systems described here will complement and/or enhance the performance o f most sensing and sampling systems. The A-Frame Mast can also support a significant sail plan for passive motion damping, silent operation underway, and increased range.

The proposed motion compensation devices will support existing technology and provide a platform which is easily adapted to emerging technologies which might otherwise go unsupported in seagoing applications. The motion compensation properties, desired to gain the greatest advantage from modern oceanographic and meteorological remote sensing and direct sensing instrumentation, are a result of the entire system designed from the hull upward including the four new systems described here.

An Optimized Catamaran Ship

The 22 meter catamaran vessel used to support these motion isolation devices was designed by Crowther Multihulls in Australia and is presented with Brett Crowther's permission (Crowther Design # 247B). The Crowther design shown in figures 1, 2, and 3 was scaled up from the pearl fishing catamaran DMB which has a fineness ratio of 11.68 and a flared hull shape. This true displacement type hull shape was evolved for sailing to minimize excessive motion which otherwise would disturb the air flow over the sails. This reduction of motion was a result of reduced water plane area, bulbous bows, and relatively broad transoms. This design maximizes usable cabin space within the hull and reduces the tendency toward pitch or roll resonance. Clearly the hull shape will be the first stage of our motion compensation approach. The computer modeling work such as that performed by Marine Dynamics discussed in section four below would aid the naval architect to inexpensively test seakeeping alternatives.

Layout Dictated by Center Well

Most ship designs are adapted from other uses with observation techniques adapted to an existing hull. By contrast, our general arrangement has been optimized for robotic, remote, and direct sensing requirements. In effect, our layout has been built around the observation techniques. Thus, the sweetest spot, the pitch and roll center, has been dedicated to a true center well and the robotic devices to be operated there. Like other research vessels, there are reinforced spots for crane, winch, and A-frame foundations. On our vessel design there are an additional four reinforced areas at the corners of the catamaran's central box structure for spud and/or davit foundations (seen in figures 2, and 3) and two reinforced supports for a central A frame or motion compensated pendulum described below. Ten scientist/crew bunks are located within each hull forward of the engine room which are accessed by two sets of stairs from the main deck. By putting accommodations within the hulls, the main deck is reserved for laboratory space over the central accommodations and engine room. The working deck aft is continuous with the center well deck under the bridge with vertical clearance for a standard 20' shipping container under the raised aft bridge and fore and aft 50' deep.

The raised aft bridge is located overlooking the two principal work areas; the deck, aft, and the center deck. Thus only one set of controls is required for navigation. Winch, center well hatch cover, spud, motion compensated pendulum (MCP), and motion compensated A-Frame Mast controls are located on the bridge. In this way, crew scientists and technicians are remote from gear launching dangers and winch and wire accidents. If roller furling sails are deployed from the A-frame/mast, the bridge is in the perfect location to observe their trim and function. Both winches and the crane are located on the 02 deck for safety and visibility from the bridge.

Straight piping and wiring ways are located in the joint between the working deck and the hull from stem to stern with direct access to all parts of the ship including deck areas, labs, state rooms and engine rooms (seen in figure 3). An additional wireway connects the individual wire ways in each hull (through the bridge deck) for power, signals, and the main electric control panel can be located on the bridge. A second connecting duct passes through the main deck between engine rooms for hydraulic and other plumbing.

Galley and mess areas are on the main deck ahead of the center deck and between the wet and dry lab spaces (Figure 2). The aft sections of the wet or dry lab can be configured for handicapped access stateroom when needed, with wheelchair access to the main deck. Stairs down through each transom give easy diver access to the water.

The Crowther design described here will meet all the UNOLS requirements for a Small Expeditionary Vessel as defined at the Fleet Improvement Committee Meeting on Coastal Oceanography in Williamsburg in early 1993. See table I below:

<u>Table 1</u>

<u>Specifications for Crowther Design #247JB</u>

Length over all	79'
Extreme Beam	34 $_{2}$
Hull Beam @ Waterline	Approximately 6.5'
Draft	4 to 4.5' Depending on Load
Full Load Displacement	62 Long Tons
Science Cargo	10 Long Tons
2 Winches Crane & Aft Frame	2 Long Tons
Center Well @ Pitch & Roll Center	8' Wide x 10.8' Long
Under Deck Clearance to Waterline 4'	Minimum @ Full Load
Scientists	16
Crew	4
Range	1,250n Miles @ 12 Knots
Duration	2 Weeks
Spud Mounting Strong Points	Set of 4 as Show in Figures 2&3
(For Lifting Vessel or Anchoring)	(In 4-15' Depths in up to 3' waves)
Marine Grade Aluminum	5083 H116 Scantlings per Det Norke Veritas
Bottom Plate Thickness	3/8"
Deck Tie Downs	1/2" NC bolt Holes on 2' Centers
Speed (Maximum)	13 Knots Power Only 20 Plus Motor Sailing
Power	Twin Diesels
Propellers (2)	Controllable Pitch
Working Deck Area Aft	450 Square Feet
Center Deck Including Well	350 Square Feet
Lab Space	640 Square Feet in Wet & Dry Labs
Optional Center Lab Module	350 Square Feet
Mooring Weights	Up to 5,000 lbs. At Stern or Center Well
Drilling and Coring	Through Center Well

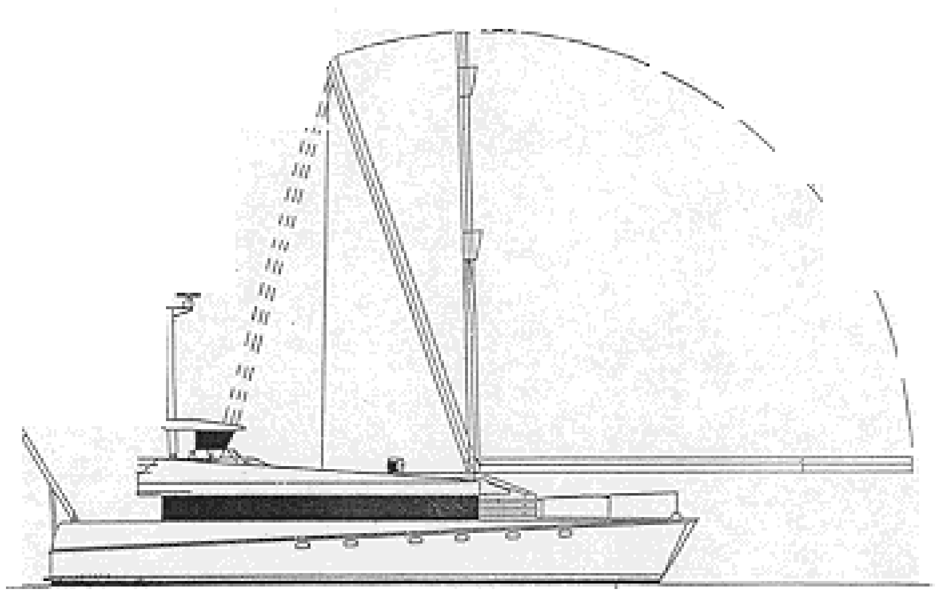


Figure 1. Profile of 79' Crowther catamaran research vessel. A-frame mast pivots about base from 20° aft to horizontal forward. In aft position A-frame may be supported by a compression strut (dashed) to the bridge top to form a tripod for heavy loads 50' over center well. In horizontal position, A-frame reaches 10 meters ahead of the vessel to deploy sensors or a conductor wire over bow for 500 lb. loads. A-frame may be hydraulically controlled in a± 15° sector to suppress pitching motion. Top of pendulum is seen in raised position (dashed) and lowered position solid. Note clean forward hull profile for minimum interference with A-frame or pendulum deployed sensor systems.

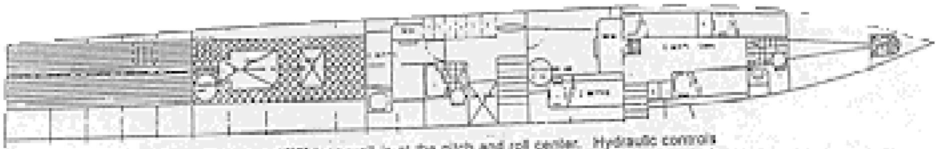
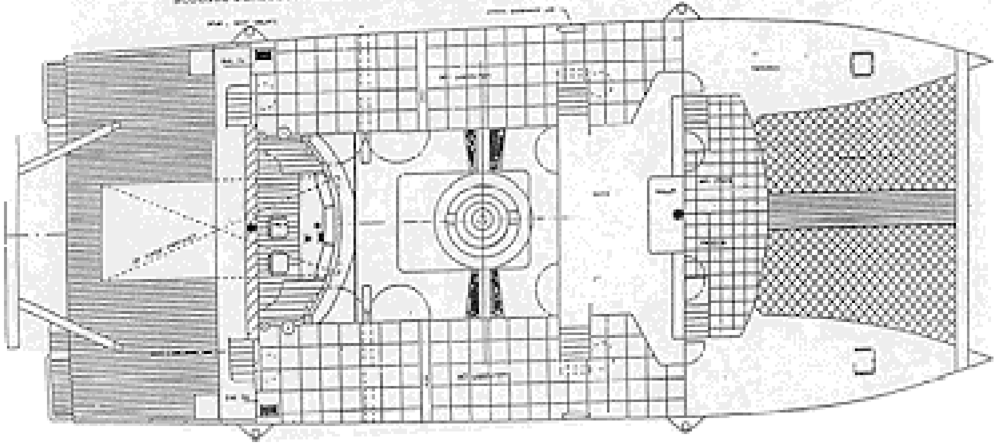


Figure 2. An 8' wide x 10'8" long well is at the pitch and roll center. Hydraulic controls fold the well cover against the forward bulkhead when the well is open. The deck surrounding the well is protected on 3 sides for work in advanced seastates. "T" shaped working deck is 34' wide aft 16' wide forward by 50' deep. Wet and dry labs have 320 square feet each and have double doors with overhead trolley onto the working deck. A 16' wide x 20' long drop in lab/accommodation module completely fills the working deck when the center well is not needed giving up to 1,000 square feet of total lab space when needed. Notice the four spud locations at the corners of the labs and the four acoustic transducer locations for true bi-static ADCP.



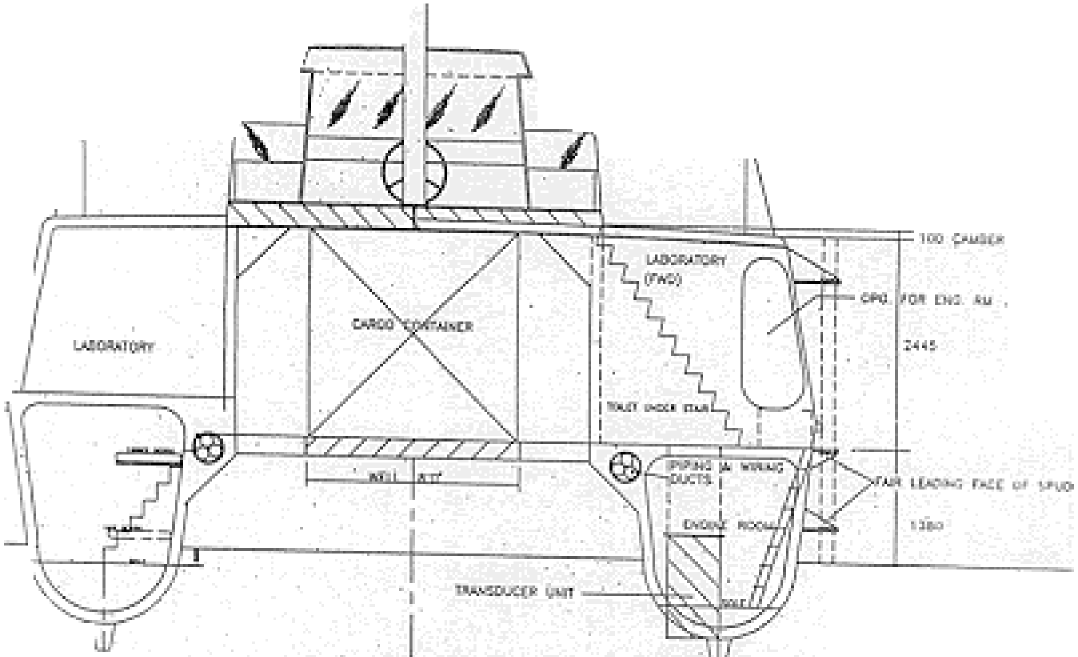


Figure 3. Mid Ship Cross Section. Note aft bridge has clearance for a standard 20' shipping container underneath. Three bolt on mounting brackets are shown for each spud/davit. Aft lab over the engine room has extra head room. In hull accommodations are under the lab with standard head room. Protective skegs/keel coolers, guard hull, propellers and tankage from grounding damage. Four 3' I.D. transducer wells are located inboard of the skegs, permitting bi-static ADCP geometry.

1) Motion Compensated Pendulum for Pitch. Roll & Heave

The pendulum system will motion compensate remote sensing devices of up to 1,000 pounds in the atmosphere, high enough to look over the forward elements of the vessel superstructure, and up to 5,000 pounds below the hulls of the vessel. Our object is to reduce the pendulum's pitch, roll, and heave motions to less than 10 percent of those experienced by the ship as a whole while operating in 4' to 8' seas. A wide variety of science missions are described below which are enhanced by the pendulum. These include: a high frequency swath mapping transducer array, side scan sonar, atmospheric radar and acoustic gear, and a small scientific drilling rig for carbonate sampling in shallow water. Conventional wire lowered instrumentation such as CTD's will also produce data with higher signal/noise and with less chance of damage or loss when handled from the pendulum.

A variety of oceanographic and meteorological sensing systems may be attached to the upper and lower ends of a motion compensated pendulum. This pendulum is located at the pitch and roll center of the conceptual catamaran. The pendulum pivots about two axes on gimbals located about 20' above the water at the 02 deck level (as seen in Figure 2). The vertical distribution of weight is such that the pendulum remains stable in a nearly vertical position when operated in a passive condition. There are mechanical stops at about +1-30 degrees in roll and +45 degrees (for towing) and -30 degrees in pitch. The pendulum will be actively controlled by hydraulic cylinders acting through the gimbal set to maintain the pendulum in a preset position in a near vertical attitude as the ship pitches and rolls around it. Pendulum inertia increases its own stability.

Pendulum Reference Data Needed for Attitude and Heave Control

A GPS Attitude Determination Unit such as the ADU2, produced by ASHTECH Inc., can allow us to measure the attitude (pitch and roll to ± .08° and azimuth to ±.04°) of the catamaran at least twice per second. These measurements are derived entirely from differential GPS data thus they are independent of the accelerations being experienced by the ship. These data are a required input to the motion compensated pendulum system and are now available for less than $20K. Such GPS systems have many uses, including the continuous calibration of the conventional gyro and magnetic compass systems, and precise location of other general purpose data. We also require the real time differential feature needed to determine position with ±1 meter accuracy and velocity to ±.l knots for ADCP corrections.

Angle resolvers mounted on the gimbals can continuously measure the attitude of the pendulum relative to the ship to within about one tenth of a degree, and are combined with ADU2 data to develop the error signals required to hydraulically maintain the pendulum in a stable vertical or inclined attitude. The addition of an accelerometer aligned with the pendulum axis allows us to develop an error signal required to hydraulically attenuate heave motion. The ADU2 is provided with a 1 meter square antenna array which is small enough to be mounted atop the A-frame mast so that it will be the highest object on the ship to avoid structural interference with satellite signals.

Trunnion Carriage

The two part (port and starboard) structure which supports the outer set of gimbal bearings is called the trunnion carriage. This carriage structurally supports a large pair of self-aligning bearings with spherical shells that hold the trunnion stubs. These stubs protrude from the port and starboard side of the outermost gimbal to permit motions about the pitch axis. It reduces the unsupported span across the center well deck so the gimbals can be smaller. An individual trunnion carriage will be needed to mount the MCP in each individual ship, or a set of adapter plates/fixtures will be required to transfer loads into the structure of each individual ship surrounding its center well or moon pool. In cases like the prototype catamaran, the trunnion carriage structure is minimized by building supporting structures into the bulkheads and decks surrounding the center well. The bulk of the carriage and gimbals are located on the 02 deck to keep the working deck clear of hardware and moving machinery. This built-in structure could alternatively support a conventional A-frame which spans this well mounted on the 02 deck, giving a 25 foot vertical working deck clearance.

The second function of the trunnion carriage is to anchor the double-acting hydraulic cylinders which move the gimbals to compensate for ship motion, friction, and hydrodynamic drag of wind or water. Control valves, hydraulic hoses, compressed air, power and signal connections, will be protected by conduits within the carriage structure with appropriate quick disconnects for easy installation/removal. Lastly when the MCP is removed from the ship, by dock crane, the trunnion carriage then becomes a storage stand simply by locking the gimbal set and the pendulum.

Other Uses for the Motion Compensated Pendulum

A lift capacity of 5,000 pounds is set for the motion compensated pendulum in order to conform to the UNOLS small expeditionary vessel heavy lifting specification. This new pendulum device is the subject of a separate patent application with the University of Miami. Since the pitch and roll center has the minimum motion on the vessel this is the ideal location to handle the heaviest loads.

A) Drilling and Coring Through the Center Well

The center well is also needed for the optimum placement of a small scientific drilling rig like the one operated by Dr. Richard Fairbanks at Lamont. His commercially produced Acker Bush Master rig has already demonstrated an additional heave compensation system (designed at Lamont) in 10' seas. His system can drill 2" diameter cores about 40 meters into carbonate sediments in water depths of 100 meters. All successful seagoing drill rigs either jack up, or are semi-submersible and/or have a true center well drilling capability.

Twenty-one foot standard lengths of drill string may be lifted from a pipe stand under the elevated aft bridge and hoisted at the top with a crown block hung at the apex of the tripod (Figure I). A system of up to four spuds is used to anchor the conceptual vessel in calm water of depths up to 5 meters, which are commonly found on the Bahama Banks and in

Florida Bay and Biscayne Bay. The MCP system can support the Acker Rig and its motion compensating system, thus reducing heaving motions another order of magnitude. A bottom plate bolted onto the pendulum base can be placed directly on the bottom in very shallow water and act as a drilling template and at the same time support the rig on the sea bed with compression loads through the pendulum body. The ship is constrained horizontally by spuds and the drill rig is free to move vertically within the gimbal sleeve. In deeper water a four anchor spread, or dynamic positioning could be implemented.

B) Five-beam Bi-Static ADCP

A downward oriented narrow beam acoustic transducer mounted at the base of a motion stabilized pendulum will make it possible to measure vertical velocities in shallow water from a moving ship. Such observations would be beneficial to a wide range of physical oceanographic, geological and biological process studies.

The advantages of the vertical transmitter beam and bi-static receiver geometry are (1) clean measurements of the vertical velocity w down to the bottom with minimal contamination from side lobes and (2) the ability to estimate the Reynolds stress (<u'w'>, <v'w'>) if the turbulent velocity (u', v', w') can be resolved. Only the vertical beam allows observations o f wand backscatter strength (related to suspended sediment and/or zooplankton) of the entire benthic boundary layer. Observations of coherent structures such as Langmuir cells, in the surface and benthic boundary layers become feasible with a bi-static ADCP. Other applications include the study of secondary circulation's related to varying bathymetry and observations of organized turbulence (Viekman et al 1994).

Because vertical velocities tend to be small, their measurement by an ADCP mounted on a moving vessel is difficult. Even small deviations from vertical orientation of the ADCP can induce an unacceptably large bias in the sensed w. This bias changes with the trim of the ship. A catamaran with a stabilized pendulum in the center well and a GPS-based attitude system will allow monitoring the orientation of the ADCP to fractions of a degree and make shipborne observations of small w feasible. Residual vertical velocity errors can be corrected with the vertical accelerometer data above or bottom reflection information.

Mounting an ADCP in the center well of a catamaran has additional benefits. There is less flow distortion than with ADCP's mounted on the bottom of the hull, there is less of a problem with bubble clouds obstructing the sound transmission, and there is minimum heave. ADCP data would clearly have much better signal/noise under rough conditions. The transducers can also be located at a shallow depth between the hulls such that measurements can reach closer to the surface than in a conventional mount or be lowered below surface bubble clouds.

C) CTD/Rossette and Other Wire Lowered Applications

Wire lowered sensors, such as CTD systems, would benefit from these motion isolation features. We can motion compensate conventional winch systems by mounting a turning block atop the pendulum with a long horizontal run of wire on the 02 deck to assure small fleeting angles. Vertical motions of the MCP produce minimal changes in long horizontal wire runs. The wire is then lead down through the center of the MCP to the CTD below. Vertical resolution would improve, mixing effects would be reduced and launching damage and personnel safety problems would be virtually eliminated. During launch/retrieval the CTD is snugged up against a compliant spring/shock absorber mounted on the base of the MCP. A conventional A-frame can be mounted on the MCP foundations, when the MCP system is not in use. Three or more restraining lines, from all sides can hold the CTD from swinging, when it is launched through the center well.

D) Diver, AUV and ROV Support Applications

Dive support platforms can be lowered by cable from the pendulum and held nearly motionless near the bottom while supplying ship resources. Examples include: two tons of steady lift, electric power, compressed air, hydraulic power and fiber optic cable for TV monitors control signals and data transmissions. Such a system would be particularly convenient to handle loads safely during underwater construction projects, which have been marginally safe in rough conditions with conventional vessels and cranes. Shark cages, decompression chambers for bell diving with decompression later on deck or other bulky safety devices could be stabilized at depths convenient to the divers mission. ROV's or AUV's could be launched through the surface under complete pendulum control (in a clamping fixture) and released at a depth of 25 feet and lowered by wire to greater depth. Retrieval is also under full pendulum control.

As an example of past problems, caused by a lack of motion compensation, both Peter Weibe and Bob Ballard of WHOI have lost ROV equipment either due to excessive wave induced strains on the tether system or collision with the ship. Sensor systems or ROV's can be held in a fixture at the base of the pendulum, until well below keel depth where wave orbital velocities are reduced and thus should escape damage. Numerous oceanographic sensors, such as CTD's, have been damaged by colliding with the hull at high velocity during launching. In order to prevent such damage, scientists, technicians and students frequently stand in harms way on a "hero platform" or under suspended loads while hanging over the side. A serious winch and wire accident involving serious inquiry has occurred in South Florida on average every 5 years.

Launching gear from the bottom of the pendulum is a robotic rather than human activity, thus personnel are remote from gear failures and gear/hull collisions. Hull/wire or wire/propeller interactions are also avoided. There will be a host of pendulum accessories, for different missions, including those yet to be conceived.

A simple pipe flange is welded to the bottom of the pendulum where the largest loads are handled. A similar bolt on flange at the top is used where atmospheric sensors can be mounted each with the same standard bolt pattern.

E) Examples of Accessories to be Developed

A water damped shock absorber/grabber, to gently capture wire lowered devices, like CTD's/Rossettes. This device would be similar to water damped mooring stops used for years on Cyclesonde moorings.

Large box cores or large diameter piston cores, for water depths 10 meters or less can be directly mounted on the MCP. These devices are pushed into the bottom, with a force supplied by the rack and pinion mechanism, which moves the pendulum vertically or a hydraulic cylinder.

F) Meteorological Pendulum Applications

The MCP would provide a unique capacity for atmospheric remote sensing. Albrecht's group currently operates a 915Mhz wind profiler and a 94GHz Doppler radar for cloud and boundary layer studies on land. Both of these systems require stabilization for ship-board applications. The 915Mhz profiler has a phased array antenna, that forms a vertical-pointing beam and two beams pointing 15° off the vertical. Winds from near the surface to 3-4 km are obtained from Doppler velocities measured along these beams. Since ship movements contaminate these velocities, stabilization is needed to ensure proper operation on a ship. The 94GHz Doppler radar is used in a vertically-pointed mode, to study cloud properties using reflectivity and the Doppler spectrum. It too requires stabilization for ship operations, since the relatively strong horizontal wind components can easily contaminate the vertical velocities, as the radar points off vertical. The MCP would have more than adequate capacity to handle these remote-sensing systems.

2) A Frame Mast for Forward Instrument Deployment -Pitch Stabilized

As part of the suite of motion compensation capabilities, an A-Frame Mast system is proposed for our conceptual catamaran ship. This system will enhance: meteorological observation, remote surface sensing, geological sampling, line of sight communication, chemical/optical sampling, acoustic noise abatement, near reef piloting, propulsion efficiency, speed and sea keeping capabilities of our conceptual vessel. Like other catamaran enhancements, the A-Frame Mast is removable. The structures to support this A-Frame Mast system are the forward spud foundations. When inclined forward, to the horizontal position, a pair o f hydraulic cylinders, bearing on the foredecks, may be controlled to remove about 90% of the pitching motion while the vessel is at rest in 4 to 8 foot seas

A) Meteorological instrument readings are adversely influenced by a ship's structure, by its disturbance of the wind field. Instruments are typically placed high on a mast to reduce these influences, but even in this case, significant corrections are often required and ship motions are amplified. Needless to say, an aft bridge location will greatly improve both direct and remote sensing meteorological of our conceptual ship. An A-Frame Mast is an extremely tall A-Frame, extending to heights of 20 meters above the water. Very narrow instrument towers can be supported from the apex, since the tower does not need to support compression loads. An A-Frame Mast, minimally obstructs the view dead ahead or above, for the bridge or for remote sensing transducer mounted on the motion compensated pendulum system. Like ordinary A-Frames, this mast is equipped with pivots, where the legs meet the deck and can be moved by hydraulic cylinders fore and aft. The legs are pivoted on the same type large self-aligning, bearings used on the gimbals. The same type of angle resolvers and double-acting hydraulic cylinder control the A-Frame Mast. A vertical sensor mast could be suspended in tension from above and lowered down to the sea surface or even below the surface. A-Frame Masts can have sufficient structural strength that they can be used without the complication and interference of stabilizing shrouds associated with conventional masts.

B) Additional Applications for a Pitch-Controlled A-Frame Mast

The use of a tall A-frame gives the flexibility of extending the measuring point well ahead of the ship and its disturbance to both atmospheric and oceanic boundary layers. Air-sea interaction measurements involve the accurate resolution of wave properties and turbulence on both sides of the interface. On conventional ships the problems (in this regard) are of two types: a) contamination o f measurements due to the motion of the ship (e.g., Katsaros et al., 1993); b) disturbance of the flow past the ship. The motion-compensated A-frame concept greatly reduces the severity of these problems, by moving the measuring point well ahead of the ship and compensating for heave and pitch of the ship.

Some of the air-sea interaction measurements that will be greatly facilitated by this motion-compensated A-frame are:
a) Wave directional spectra using an array of remote (laser) ranging devices (Donelan et al., 1996).
b) Momentum, heat and mass fluxes across the interface.
c) Infra-red sensing of the surface skin.
d) Wave breaking statistics.
e) Turbulence structure on both sides of the interface +/- 5 m (Terray et al., 1996).

C) Geological Sampling Uses of an A-Frame Mast

In the aft position, the apex of the A-Frame Mast would be directly over the center well and could be used to support a crown block to hoist standard 21' sections of drill string for Fairbank's heave compensated drill rig. For heavier loads, like vibra-coring, a compression strut could be installed from the top of the bridge deck to join the A-Frame to form a very rigid tripod. (see Figure 1) The greater mast height could provide exceptionally long core capability in soft sediment environments (up to 2 O meters or more) when the vessel is spudded in place.

D) A Third Wire Deployed Forward for Chemistry and Optics

In a forward position, a third wire for loads up to 500 pounds could be rigged through a block at the A-Frame's apex. This would permit the deployment of wire lowered sensors 10 meters ahead of the ship's influence. This would reduce ship shadow for effects optical sensors such as those deployed by Rod Zika or Ken Voss. If the forward section of the ship is primarily netting rather than solid structure, there will be even less influence by the ships shadow. This third wire conforms to a small expeditionary vessel specification by UNOLS to be able to deploy up to three, widely separated, wires simultaneously for independent experiments. In this way three independent groups with different wire requirements could make complementary measurements without interference. One wire is deployed over the stern A-frame, the second wire is deployed through the center well, and the third wire is deployed over the bow supported by the A-Frame mast. This would give about IS to 20 meters separation between the wires. The A-Frame Mast would be much simpler to use than conventional outriggers since it is little more than an oversized A-Frame. These wire-lowered sensors would also be stabilized in pitch ahead of the vessel.

E) Navigational. Propulsion and Seakeeping With an A-Frame Mast

In the horizontal position, the A-Frame Mast can pass under low bridges. A pivoting crows nest, can support an observer ahead of the ship when navigating coral strewn waters to look downward for obstructions without critical angle of reflection problems typically experienced from the bridge. At night, underwater lights looking forward from the bulbous bows of each hull, will provide illumination at a time when ships are typically blind underwater.

The upper crows nest would provide a convenient mount for instruments and a convenient platform to service: the crown block, upper bearings for roller furling gear, and scientific instruments. A tensile member is located along the aft edge of each mast extrusion (not shown in Figure I) to support the mast in its extreme forward position. Compressive struts between the tensile member and the mast will be spaced at convenient intervals to form steps to climb the A-Frame Mast, with a track for a clip-on safety harness to protect workers aloft.

When not in use for remote sensing, the A-Frame Mast could support a significant sail plan. This offers a capability of taking acoustic data with complete silence from rotating machinery. Seismic or bio-acoustic uses are possible with minimum noise while underway. This would be a unique capability in the entire UNOLS fleet. Sails will result in greatly improved catamaran seakeeping, which will be invaluable when crossing or working in the Gulf Stream during strong North winds. Comfort and range will be improved while making long transit legs to or from the Caribbean Sea across the trade-winds, or crossing from Key West to Cuba after it opens up. John Adams, President of Motion Dynamics Inc., believes Catamaran motion reduction by sails is a re-emerging technology, which may prove more effective than computer controlled fins at low speed (personal communication). Motion Dynamics can do computerized sea keeping model runs including sails to demonstrate their effectiveness quantitatively. Intelligent use of sails while motor sailing will improve speed (about 50% under favorable conditions) and increase the range of the vessel, without burdening the catamaran with added tonnage of fuel.

Recently, a mono-hulled concept boat "Amoco Procyon", has demonstrated a similar full height bi-pod mast. This reduced weight aloft by 25% and windage aloft by taking advantage of carbon fiber in a system designed, built and patented by Eric and Ben Hall at Hall Spars. This system can be raised and lowered, to allow a 30 meter mast to be lowered to 20 feet above the water, to permit passage under low fixed bridges. This bi-pod mast permits hydraulic roller furled sails for both jib and mainsail for ease of short handed sailing on this 65' long high performance boat. Hydraulic roller furling on all sails greatly reduces crewing requirements on motor sailing vessels, so that they are about the same as powered vessels. The Procyon carries 40% more sail area than comparable boats and has greater mainsail efficiency because it is not in the turbulent wake of a conventional mast. The above improvements are calculated to increase boat speed about 10% compared to other ULDB boats.

The advantage of motor sailing would be far greater on a catamaran with 34 foot beam for a wider A-Frame Mast foundation plus much wider sheeting angles. The righting moment is calculated to be a 2 million + ft-lb. and a much higher 25 + knots hull speed. See Van Leer (1982) for a more detailed discussion of Sailing Catamaran Research Vessels.

3) Shallow Water Motion Stabilization With Spuds - A Proven Technique

Barge-like hulls have been traditionally used in shallow water to minimize draft and maximize payload. As long as the footprint of the barge is large enough to span several wave lengths of the dominant gravity waves, the motion response of this platform will be minimal. The ultimate improvement in shallow water barge motion can be had by jacking-up the barge so that the hull is raised completely above the gravity wave crests. This approach has been successfully used at RSMAS by Dr. R.N. Ginsburg and others to drill on the Bahama Banks in the self-propelled Jack-up Mobile Platform (JUMP). However the maintenance of this specialized platform, or the marshaling costs to bring such a vessel from Louisiana prior to each use, precludes ownership or use, except by a large scale project with enough recurring use to keep the platform employed nearly full time. See Van Leer (1985) for other jack-up catamaran ideas.

In Biscayne Bay, construction barges are anchored by using two or more spuds. These spuds are typically long steel pipes, deployed through a clear hole in the deck, lined with a larger internal diameter pipe, which passes through the barge and out the bottom. A central crane on the barge, lifts each spud clear of the bottom so it may be locked in the up position before the barge is moved to a new position by tug boat. We describe a similar spud system to anchor our catamaran below.

Spud Anchoring System for Shallow Water Motion Stabilization

Our concept of a shallow water anchoring system, consists of a set of two or more spuds, carried within fixtures which bolt on any or all o f the four corners of the catamarans rigid central structure, as seen in Figures 2 and 3. A simple sleeve style bolt on fixture can be designed to transfer the load from each spud into the catamaran structure. Each spud is equipped with a rack and pinion drive to move the spud up and down. Hydraulic controls may be located on the bridge and/or directly next to spud mount, on the 02 deck. The pinion drives a rack which is welded to the side of the spud. In this way, a crane and operator is not needed, to deploy or recover the spud, since a crew of two may be called upon to operate our vessel.

For the first generation system described here, we will use standard design small sized jack-up platform legs, made of aluminum, with a single standard hydraulic planetary gear drive and locking mechanism. The wall thickness of the tubular spud, will be chosen, so that it will bend or break before damaging the vessel's structure. A small water pipe can be built into the center of each spud, to break any vacuum which might prevent the spud from being extracted, or to bury the spud end to a depth of a foot or two. We suggest bolting on these spuds to:
a) prevent a bent spud from jamming in a hole through the deck, since it may be unbolted and removed by crane,
b) completely remove spuds when not in use, to reduce the science cargo in favor of other instrumentation or equipment,
c) install other devices like: air gun davits, large outriggers, folding antenna's for OSCR (Ocean Surface Current Radar), king posts for trawling, or large acoustic transducer mounts could be temporarily installed. The same NATO/UNOLS standard 2' square bolt pattern will be built into the side of the vessel's main box structure as are found on working decks. We envision using spuds in protected waters, or in conditions where wave heights are less than 3 feet and water depths are less than 5 meters. If four spuds with rack and pinion drives are installed, the vessel could be jacked up for maintenance or operations in calm conditions. Most large catamaran and swath vessels have four reinforced strong points so they may be lifted by slings for launching. There are frequently width limits in marine railways and ready availability of large cranes in most seaports.

4) Controlled Fins as an Active Part of a Motion Isolation S):stem

SWATH style vessels are widely regarded as having the best seakeeping properties. It should be noted that seakeeping on most SWATH vessels, while underway, is improved significantly by four or more stabilizing fins. These fins are hydraulically actuated and computer controlled, such as those used the Monterey Bay Aquarium SWATH. Such systems are designed commercially by Maritime Dynamics Inc. in Maryland. About 50 systems, delivered by Maritime Dynamics, were installed on conventional high-speed catamarans, where their computer modeling is highly evolved. Heave and pitch motions are said to be reduced by about 50%. Costs for systems appropriate for catamarans in our size and speed range vary between $250K and $350K. Such a fin system should be considered for extensive high speed underway surveying applications. We suggest the installation of such a system in our conceptual catamaran vessel. The computer modeling part and design o f this system is essential to the design of the remaining 3 motion isolation systems. Since the hardware is well proven, the structure needed to mount the fins can be built in at reasonable cost with additional funding later for complete installation. Response of our chosen hull form, to random wave excitation, will need to be modeled on five representative courses relative to the dominant wave direction. These response functions will be essential to the design of the MCP and A-Frame Mast control systems as their first stage of motion compensation. These response functions will also help us plan operations in ways that take the greatest advantage of what a well- designed catamaran has to offer. Ultimately after the fins are installed, data from their controller will be available to our controllers through the

LAN. At speeds of a few knots, the fins become ineffective aside from a little passive damping.

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Figure 3. Mid Ship Cross Section. Note aft bridge has clearance for a standard 20' shipping container underneath. Three bolt on mounting brackets are shown for each spud/davit. Aft lab over the engine room has extra head room. In hull accommodations are under the lab with standard head room. Protective skegs/keel coolers, guard hull, propellers and tankage from grounding damage. Four 2' I.D. transducer wells are located inboard of the skegs, permitting bi-static ADCP geometry.