REMOTELY-OPERATED VEHICLES FOR RESTRICTED-ACCESS HYDROGRAPHIC SURVEYS

Lead Author: Jeffrey Z. Snyder
SeaVision Marine Services LLC
302 Maple Hill Road
Naugatuck, CT 06770 USA
jsnyder@seavisionmarine.com

Co-Author: Matthew Cook
SeaView Systems Incorporated
9890 Huron Creek Drive
Dexter, Michigan 48130
mcook@seaviewsystems.com

Co-Author: Richard Hallyburton
CD Limited
Silverfield House
Claymore Drive
Bridge of Don
Aberdeen, Scotland AB23 8GD
rh@cdltd.net

ABSTRACT

Inshore, vessel-based hydrographic survey techniques typically draw upon data from satellite positioning systems to provide xy-positioning control. These survey techniques encounter significant obstacles, literally and figuratively, during surveys in restricted access environments such as under piers or moored vessels.

The accessibility afforded by an inspection-class ROV and the accurate xyz positioning provided by an onboard Inertial Navigation System (INS) make it possible to overcome the issues that accompany hydrographic surveys in restricted access environments. By carefully applying this technology with an appreciation for principles of hydrographic survey techniques, it is possible to supplement traditional vessel-based hydrographic surveys with ROV-based surveys.

INTRODUCTION

Presently, satellite global positioning systems (GPS) provide excellent positioning information for a variety of applications. In the practice of hydrographic surveying, a survey vessel can be positioned so that measured depths can be paired to recorded xy-positions to generate bathymetric models of the seafloor, river bottoms, harbors, berths, etc.

What happens when we cannot gain access to the GPS data from satellites because our view of the sky is obscured? How can we measure depth information that may be critical to an engineering, construction, or navigation project when we cannot gain access to the survey area with a vessel?

For the purposes of this discussion, we shall collectively refer to these circumstances as "restricted-access hydrographic surveys". The focus of our exploration shall be inshore areas such as piers, platforms, and moored vessels that obscure the bottoms of water bodies that must be surveyed. In looking at these challenges, we shall briefly review some existing approaches to surveying these areas that may be inadequate, and describe a demonstration of a proposed alternative approach that involved a remotely-operated vehicle (ROV) fitted with an inertial navigation system (INS).

RESTRICTED ACCESS SITUATIONS

In the inshore, particularly in developed ports and harbors, there exist a variety of structures that prevent access to certain portions of the water by vessels, and obscure a clear view of the sky for GPS systems. Piers, relieving platforms, piling-supported platforms, bulkheads; all may cover a portion of a body of water, and that portion of the water may only be accessed by divers or remotely-operated vehicles. There may also exist moored vessels, drydocks, or barges that for one reason or another cannot be easily moved to clear an area for a survey.

In the design and/or construction phase of any project, it is often necessary to determine the mudline elevations of the bottom adjacent to structures and especially where the bottom may be obstructed by these structures. Bottom elevations can figure into models to calculate appropriate design loads for structures, be used to calculate necessary dredge or fill volumes, or determine whether a vessel moored for an extended period of time may be moved from its mooring with or without dredging.

It may be convenient, under a pier or platform, to assume an existing slope based on knowledge (or perhaps a guess) as to the sediment stability under the structure. Clearly, this may be risky from a design standpoint because little to no information may substantiate the assumption.

As many of these structures are inspected by divers, two diver-based techniques may be used during the inspections: hand measurements or pneumo-fathometer readings. If the structural plan for a given structure is accurate, then spot elevations of the mudline at specific locations under a structure may be recorded by using direct measurements between the mudline and known components (such as a pile cap, or perhaps decking, etc.) that have a known elevation relative to a project or geodetic datum.

Divers may make spot mudline measurements where reference points such as pilings can provide xy-positioning to be paired with the depth measurement. These measurements may be made by hand with rulers or sounding tapes, or with pneumo-fathometer measurements take at the mudline and corrected for tide elevations after the inspection.

Where project depths preclude easy hand-measurements, tide measurements may be recorded independently and pneumo-fathometer readings at the mudline may be recorded as spot elevations. These observations may later be corrected for tide. Unfortunately, this approach is only precise to within 0.5 feet vertically, and the accuracies of the method may be suspect depending on the calibration of the pneumo-fathometer system.

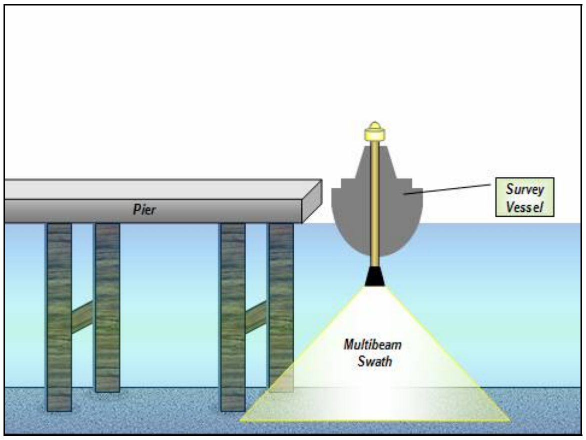
Both diver-based approaches suffer from significant deficiencies in data density as there are only so many measurements that a free-swimming diver may make in a given period of time. And of course, divers are susceptible to factors such as poor visibility, strong currents, and human error that could adversely impact the accuracy of any measurements taken. Truly accurate horizontal positioning remains difficult as it is highly dependent on the accuracy of the as-built structural plans of the structure.

Depending on the project, a sparse bathymetric data set with known positioning inaccuracies under a pier may be sufficient to develop intelligent assumptions that meet the demands of the project. However, some projects demand more accurate, dense data in order to properly manage design protocols and cost estimates.

In order to overcome the lack of data density and the accuracy issues that may accompany diver-based survey techniques, vessel-based hydrographic surveys may be considered. Global positioning system (GPS) technology provides highly accurate, real-time positioning that can be paired with bathymetric data via automated software applications to generate underwater topographic models.

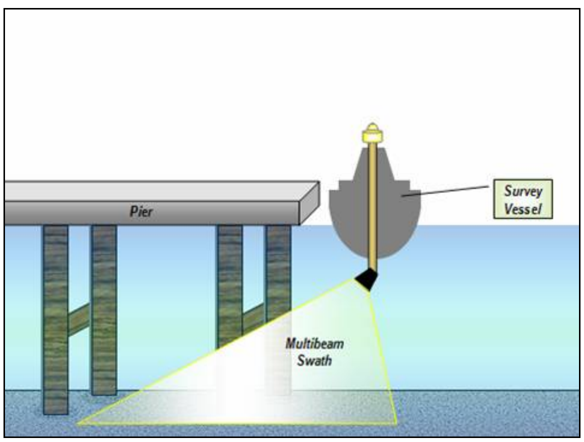
It is relatively safe to say that most hydrographic surveys, in open water, rely upon a GPS receiving system, a downward-aimed hydrographic survey echosounder (either single-beam or multi-beam), and survey software packages (such as Hypack or WinFrog). Additional pieces of equipment, such as tide gauges, sound velocity profilers, and motion reference units may round out the survey spread in order to measure tidal water elevations relative to a project vertical datum, account for the velocity of sound to get accurate distance measurements between the echosounder and the bottom, and correct soundings for motions related to vessel heave, heading, pitch, and roll. The aim of these surveys is to develop underwater topographic models that consist of accurate horizontal positions paired with accurate vertical bottom measurements.

On the occasions when a hydrographic survey must be performed in a restricted-access situation, it may be possible to utilize swath multibeam echosounders or profiling sonars from surface survey vessels to collect data under the structures. A portion of the footprint under a pier or relieving platform or moored vessel may be "illuminated" by the swath of the multibeam transducer or the profiling sonar when the sonars are configured in their typical downward orientation.



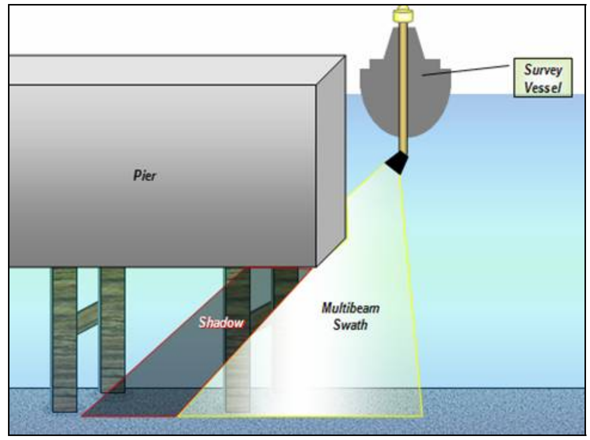
Measuring the bottom elevation near a pier with a swath multibeam bathymetric system.

It is possible to increase the size of the footprint that is covered in this survey approach by rotating the multibeam or profiling transducer off-axis. So long as the angle of rotation is accurately measured, survey software can be configured to accommodate the axial rotation and the result can be a very dense, accurate bathymetric data set in a restricted-access environment that references an accurate horizontal and vertical datum.



By tilting the echosounder, it may be possible to expand the survey footprint under the pier.

Unfortunately the size of the footprint available for survey may be limited by the inability to "see" the footprint with the survey transducer. There is the flexibility to rotate the transducer so that it directs more of its swath towards the area beneath a structure. However, no amount of rotating a transducer can overcome the fact that the relative elevations of the transducer, the obstruction/structure, and the bottom profile can create a "shadow" that prevents survey beyond it and thus reduces the total footprint that can be surveyed. The maximum depth of the structure can thus create a "shadow" which can only be overcome by dropping the survey transducer beneath this maximum depth.



A pier deck that extends well below the water level creates a "shadow" for the multibeam swath that cannot be removed without dropping the depth of the transducer.

The deeper that this maximum depth exists beneath the water surface, the more that the feasibility of using a vessel-mounted survey system dramatically decreases. The operational and safety considerations of having a large over-the-side mount reaching to significant depth and attached to a small inshore survey vessel make these approaches less attractive.

SPECIAL PROJECT DEMANDS ALTERNATIVE

In late 2005, the Naval Inactive Ships Maintenance Office (NISMO) approached SeaVision Marine Services LLC (SeaVision) to conduct a hydrographic survey of the berths at Pier 1, Naval Station Newport, Rhode Island. The berths, located north and south of the pier, are home to the decommissioned aircraft carriers *USS Saratoga* and *USS Forrestal*, respectively.

NISMO, charged with maintaining the U.S. Navy's decommissioned vessel fleet, wanted to learn the bathymetric conditions under and around the carriers prior to any plans to permanently move the carriers from their moorings. Moving the vessels from their berths temporarily to complete this latest survey was considered prohibitively expensive and risky. Both vessels were moored to the piers with heavy weather, long-term moorings that would be costly to undo. The previous surveys of the berths had been performed in 1998, and the underwater conditions in the berths since then were unknown, risking a possible grounding of the carriers.

The pier measures approximately 1575 feet in length and the survey footprint of each berth was approximately 1900 feet by 400 feet. Each aircraft carrier measures approximately 1000 feet in length with a maximum beam at the waterline of 130 feet, and current drafts in the neighborhood of 30 feet beneath the waterline.

The stern of the decommissioned aircraft carrier USS Forrestal at Naval Station Newport, RI. The mooring lines and chains for the long-term heavy-weather mooring configuration, and the hull itself, prevent survey of the bottom underneath the footprint of the carrier by a vessel.

The dimensions of the survey areas and the carriers are particularly important when considering the objectives of the survey, which were two-fold. The primary objective was to survey the entirety of each of the berths, including the footprints under each of the carriers. The secondary objective was to determine the distance between the hulls and the mudline based on the existing draft conditions at the time of the survey.

Several options were considered for conducting the survey. Each option consisted of a traditional, vessel-based hydrographic survey with a single-beam echosounder in the accessible portions of the berths. To address the footprint under each moored aircraft carrier, diver and remote techniques were considered.

Diver investigations of the entire hull were considered ineffective as a standalone solution because the data scarcity would be unacceptable to the project, and the horizontal positioning of divers under the hulls would be problematic due to the sheer size of each hull and the difficulty in providing accurate landmarks to the diver.

Remote methods, such as surveying with a multibeam echosounder were also considered. Clearly, the technology could provide an outstanding data density and the survey quality would be highly accurate.

The beam of each aircraft carrier was 130 feet, and the draft was approximately 30 feet. Surveying from the surface with a multibeam echosounder was predicted to produce a coverage of about 15% of the footprint under each aircraft carrier. The carriers' drafts of approximately 30 feet also meant that rotating the transducer at the surface would not produce any appreciable effect on increasing the survey footprint.

The only way to increase the coverage of the survey footprint would be to drop the transducer in elevation to near 30 feet so that the transducer could be rotated in order to transmit under each vessel. This approach, too, was considered unacceptable because it would be very difficult and potentially unsafe to survey with the multibeam echosounder on a pole mount extending nearly 30 feet below the water surface. It was also a concern that, even if we could drop the transducer to 30 feet of depth, the massive beam of the carrier would still prevent us from surveying the entire footprint.

Taking into consideration the size of the carriers and the accuracy and density of bathymetric data that the project required, the survey required aspects of both diver and remote approaches. We needed the ability to gain access to the complete underside of each aircraft carrier so that we could collect bathymetric data within the footprint of each carrier. We also needed the positioning accuracy and the data density that a traditional vessel-based survey strategy would provide in accessible waters.

Our attention turned towards using a remotely-operated vehicle (ROV) as a survey platform. An ROV, with its power distribution and data transmission capabilities, could be deployed with a sonar profiler in order to collect bottom elevation information throughout the survey footprints in the restricted-access portion of the berths. SeaVision reached out to ROV services provider SeaView Systems, Incorporated (SeaView). It was determined that a SeaEye Falcon DR afforded an ideal survey platform that could give us the flexibility to gain access anywhere within the survey footprint under each aircraft carrier.

Two parts of the equation, access and vertical measurement, could be addressed with the ROV. The challenge remained to accurately position the ROV so that we had a bathymetric model of the floor of each berth that resembled a traditional hydrographic survey. Acoustic positioning methods such as ultrashort baseline (USBL) and long-baseline (LBL) were discounted out of concern that the minimal clearance between the carrier hulls and the bottom would create multi-path issues that might adversely affect the horizontal and vertical positioning solution.

It was determined that an aided inertial navigation system (INS) could provide us with real-time, accurate horizontal and vertical positioning in order to properly track the ROV through the surveys and provide an attitude and heading reference for the profiler mounted on the ROV. SeaVision and SeaView reached out to CD Limited (CDL), a developer of subsea positioning and sensing equipment, to supply an aided inertial navigation system that could be mounted to the SeaEye Falcon ROV.

AIDED INERTIAL NAVIGATION

The CDL MiniPos is an INS that is built around a Kearfott Ring Laser Gyroscope (RLG). A monolithic RLG provides highly accurate heading, pitch, and roll information in real time at a rate of nearly 20 Hz. This information, when paired with the data from linear accelerometers in three dimensions (x, y, and z) can produce an accurate dead-reckoning position for the INS in three dimensions.

The inner-workings of an INS can seem a bit "black-box". However, if we think back to our college-level physics, an instantaneous measured acceleration can be integrated with respect to time to generate a velocity. Removing the calculus notation, the equation is:

$$v_t = v_0 + (a_t \cdot \Delta t)$$

This is read as: the velocity at any time *t* is equal to a starting velocity plus change in velocity due to an acceleration applied over an incremental change in time *t*. A second integration can generate a displacement.

$$x_t = x_0 + (v_t \cdot \Delta t)$$

such that the location *x* at time *t* is equal to a starting location plus a change in location due to the velocity over an incremental change in time *t*.

Unfortunately, a stand-alone INS has a tendency to drift because it does not sense constant velocity drift. Without aiding from an external source, an INS can only generate its own values for the constant velocity (the v_0 member of the equation above). The INS struggles to accommodate three-dimensional long-term drift, so CDL aides the MiniPos by providing it with an RD Instruments Doppler Velocity Log (DVL) and Druck pressure sensor.

The DVL provides real-time constant velocity measurements that aid the INS to account for horizontal (xy) drift. The Druck pressure sensor, accurate to nearly 0.04% of actual depth, provides a vertical correction to aid the INS. These inputs, combined with the dead-reckoning solution from the RLG and linear accelerometers, are fed through onboard hardware and firmware that run a series of Kalman filtering algorithms that generate the aided inertial navigation solution.

The pairing (the INS and the DVL) mounted to an ROV instrument skid are run through a "training" or calibration routine prior to the actual survey so that the Kalman filters can be taught how to combine the information from the INS and the DVL to generate a highly accurate positioning solution. After calibration, the result is an instrument skid that is ready to be mounted to the underside of the ROV (in our case, the SeaEye Falcon), powered from the ROV, and capable of outputting a single data stream that contains the x,y,z positioning, the heading, pitch, and roll and the velocity of the ROV in real-time at an update rate of between 10 Hz and 20 Hz.

The SeaEye Falcon DR, fitted with an instrument skid that has the CDL MiniPos INS and RD Instruments Workhorse DVL mounted. The calibration routine is actually performed with the skid separate from the ROV, towed from a survey vessel, so that a variety of velocity changes, angular accelerations, and turns can be performed quickly in order to train the Kalman filtering algorithms in the INS.

So long as we know the real-world location (in coordinates) of our starting point, we can use the aided INS to generate a displacement from the start-point that takes into consideration the entire course traveled, because each position solution is a function of the previously recorded position. The added benefit of the aided INS is that, with an RLG at its core, it can provide very accurate heading and attitude referencing to correct for the attitude of the ROV and thus any onboard profiling sonars.

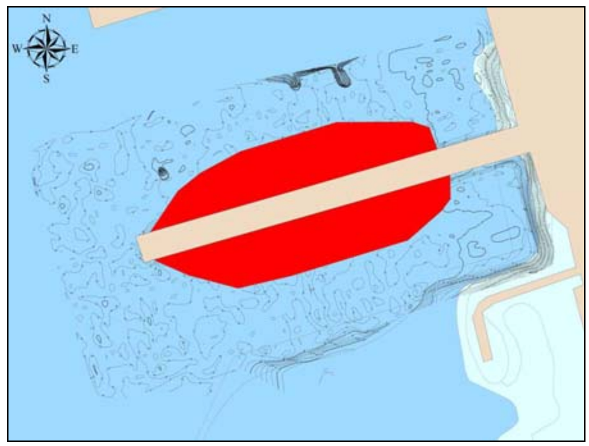
SURVEY OPERATION

SeaVision performed the survey of the accessible portions of the berths at Pier 1 from a small survey vessel. We utilized an Innerspace 455 200 kHz Digital Survey Echosounder and paired with Trimble DSM 132 Differential GPS. Hydrographic survey data was collected in accordance with the provisions for a general condition hydrographic survey as described by U.S. Army Corps of Engineers Hydrographic Survey Manual[1].

NMEA-0183 strings from the DGPS were captured through the Hypack survey acquisition software and converted to the North American Datum of 1983, Rhode Island State Plane feet. Tidal elevations were measured at a nearby NOAA tide station to provide corrections for tide relative to Mean Lower Low Water (MLLW), and sound velocity corrections were applied by performing bar check calibrations with an Innerspace 443a Digital Sound Velocity Profiler. Survey profiles were collected with a track spacing of 25 feet, perpendicular to the pier face in each berth, and several checklines parallel to the face of the pier (thus parallel to the length of the aircraft carrier) were conducted on a spacing of 100 feet on each side of the pier.

A docking garage, similar to the one shown with this SeaEye Falcon, was deployed adjacent to the pier to provide a known starting and ending reference point for the ROV prior to and after the ROV-based survey under the carriers.

Divers from Halcrow/HPA assisted SeaVision by placing a docking garage at the offshore tip of the pier at an elevation of -31 feet MLLW. The diver positioned the skid and a plumb line from which a static DGPS position and the elevation of the center of the docking skid could be measured. Divers also checked point soundings at critical locations (deepest point of the propellers and rudder posts) on each of the carriers. Time and tide measurements were recorded so that all diver-measured elevations could be corrected for tide and referenced to MLLW.



The vessel-based hydrographic survey at Pier 1, Naval Station Newport, was used to develop 1-ft elevation contours in the berths surrounding the pier. The area in red represents the footprints in both berths where the aircraft carriers or their mooring hardware restricted access by the survey vessel.

For the restricted-access survey, we attempted to mimic a traditional vessel-based hydrographic survey approach. To do this, we required:

(1) accurate horizontal positioning
(2) accurate transducer draft (or in this case, vertical positioning)
(3) measurement from the transducer to the bottom
(4) corrections for sound velocity
(5) corrections for tide elevation
(6) real-time navigation and tracking to monitor date coverage and density.

To this end, we paired the CDL MiniPos aided-inertial navigation system (and the RD Instruments Workhorse Navigator DVL) with a CDL MiniPulse profiling sonar. This satisfied our requirement for accurate horizontal and vertical positioning of a profiling sonar transducer that could make measurements between the transducer and the berth bottom. Tides were recorded relative to MLLW at the nearby NOAA tide station, and sound velocity measurements were taken with the Innerspace 443a sound velocity profiler and used to correct the soundings from the MiniPulse profiler according to sound velocity conditions. The full survey spread was mounted to the instrument skid on the SeaEye Falcon to give us full access to the restricted portions of the berths, and real-time positioning was fed into Hypack so that we could control the survey progress and monitor bottom coverage.

Initial deployment of the ROV with the survey spread required the ROV to set in the docking garage for approximately 1 hour prior to the survey activities. This allowed the ring laser gyro time to settle on true north and also provided the INS with a known start location from which all further positions were generated.

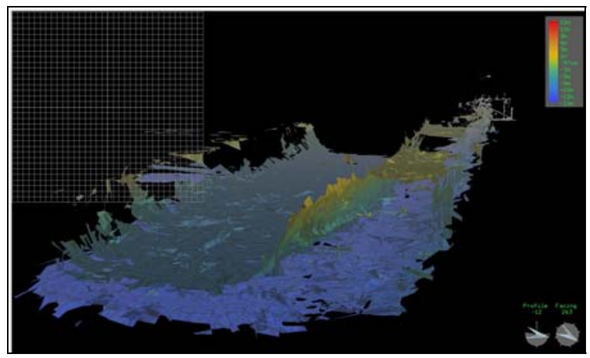
From the garage, the ROV was directed along pre-planned survey lines under each aircraft carrier with line spacing based on the swath width of the profiling sonar, suitable overlap between lines, and the footprint that was not surveyed during the vessel-based survey. The real-time positioning from the INS, fed topside via the umbilical to to a control computer and imported into Hypack, allowed the ROV pilot to navigate the ROV on each of the survey lines. Care had to be taken to avoid fouling in the cathodic protection system in place on each aircraft carrier Care also had to be taken to maintain an elevation of 0.3 meter or better above the bottom so that the DVL could properly track the bottom and feed the velocity drift corrections to the INS. Clearly, survey operations at high tide were preferred because they afforded the greatest separation between the hulls and the bottom.

The profiling sonar was configured to collect data in a full 360-degree vertical profile circle around the ROV and profile both the berth floor and the hull so that bathymetric soundings of the berth could be compared with actual elevations of the hulls to determine under-keel clearance.

Periodic follow-on dockings throughout the progress of the survey, of approximately 5 to 10 minutes per docking event, allowed us to observe the performance of the INS and re-set the position to the known dock location, thereby minimizing long-term positioning errors and maintaining the horizontal positioning error to 1 meter or less, which is consistent with the accuracy generated by the Trimble DSM 132 Differential GPS used during the vessel-based survey.

SURVEY PROCESSING AND DELIVERY

CDL had previously prepared this instrument package for a flooded tunnel inspection and modeling effort in the Middle East. We worked with CDL to modify the data collection routines in order to better accommodate a hydrographic survey project. We used CDL's Tunnel Mapper acquisition software for data collection and integration. All time-stamps, offsets, position, attitude, and position (both horizontal and vertical) were recorded topside for later post-processing to generate a geographically referenced bathymetric data set. The data, when integrated in the CDL Tunnel Mapper software and brought into the CDL Tunnel Viewer software, created a three-dimensional, geographically referenced data set of bottom and hull elevations.

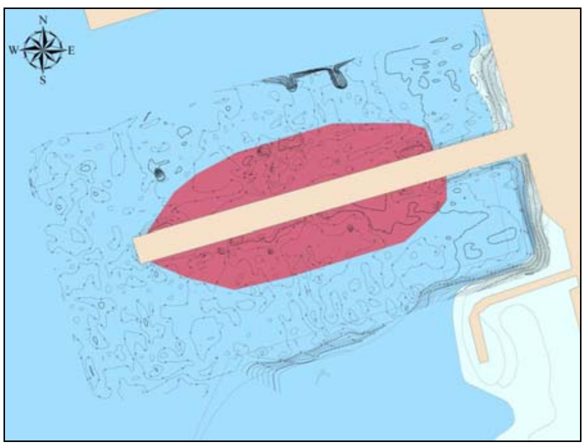


The raw data from the survey merged both the berth floor data and the hull data into a 3-D image model within CDL's Tunnel Viewer software (developed for flooded tunnel inspections). Notice the sloping wall of the hull of the aircraft carrier, and the slope approaching the vertical feature on the right – where the berth meets the slope under the pier.

For our purposes, we needed to separate the hull elevations from the bottom elevations so that the bottom elevations could be corrected for tide and referenced to the project datum of Mean Lower Low Water. To do this, we developed custom software that would read the standard CDL file format and first separate the hull data from the bottom data. This was rather easy, simply by looking at the profiling sonar bearing and creating separate data files according to when the sonar pointed up (for the hull) or down (for the bottom).

After separating the data sets, we used Hypack to generate a tide correction file that tracked the tidal elevations relative to MLLW. We then subjected the bottom data set to a look-up algorithm where the time stamp of the profiler data was compared to the time of tide, and the depth of the ROV was corrected according to the height of tide at each time. Note that the hull data was not subject to tide corrections, as the elevation of a floating hull is independent of the vertical datum; the elevation is a function of water level and vessel loading.

After correcting the bottom data sets for tide, we imported the hull data and the bottom data back into CDL Tunnel Viewer in order to export geographically referenced xyz bathymetric data of the bottom and the hull. The CDL Tunnel Viewer exports data in the Universal Transverse Mercator (UTM) grid, so we used Hypack to convert into the project horizontal datum of NAD 1983 Rhode Island State Plane feet. There, the bottom elevation data collected with the ROV from underneath each of the aircraft carriers could be merged with bottom elevation data during the vessel-based hydrographic survey. The combined data was then presented to in a series of deliverable drawings consisting of plotted soundings, plotted contours, and differential plots illustrating the under keel clearance between the hulls and the bottom at Mean Lower Low Water.



The total hydrographic survey at Pier 1, Naval Station Newport, was used to develop 1-ft elevation contours in the berths surrounding the pier. The area in red represents the footprints in both berths where data collected with the ROV (armed with an aided INS and profiling sonar) completed the restricted-access portion of the survey.

Some statistics, comparing the results of the vessel based hydrographic survey have been performed to determine the correlation of the vessel-based hydrographic survey with the ROV-based hydrographic survey. The standard deviation of the overlapping soundings was 0.5 feet or less. Sixty percent of the overlapping soundings fell within one standard deviation, and ninety-five percent fell within two standard deviations. It should be cautioned, however, that we only had twenty-one soundings where overlap occurred; while the statistics are promising, they are hardly conclusive.

CONCLUSIONS

For a recent hydrographic survey adjacent to two decommissioned aircraft carriers, a standard, vessel-based hydrographic survey would be restricted from accessing significant portions of the berths due to the carriers and their mooring hardware. The carriers could not be moved from their berths to accommodate the survey, but it was necessary to survey under the carriers in order to supplement the bathymetric data collected during a traditional vessel-based hydrographic survey.

It was determined that divers alone would not be sufficient to accurately determine the bottom elevations under the carriers. Difficulties in accurately positioning the divers horizontally and vertically, and very sparse data, led us to conclude that divers would not provide enough high-quality data to properly supplement the vessel-based hydrographic survey.

Mounting a swath multibeam or profiling sonar system was considered for this project. However, the draft of the carriers at 30 feet, and the beam at the waterline of 130 feet, prohibited the use of a vessel-mounted sonar system that could be rotated to more directly survey under the carriers. Though this approach could provide accurate data with high-quality horizontal and vertical positioning for the soundings, large portions of the survey footprint under each carrier would be left without survey coverage unless we mounted the transducer near 30 feet below the water surface. This was deemed to be unnecessarily difficult and potential hazardous to the survey vessel and equipment.

To complete the survey under each of the aircraft carriers in this restricted-access environment, SeaVision Marine Services LLC teamed with SeaView Systems, Incorporated to deploy a remotely-operated vehicle armed with an aided inertial navigation system and profiling sonar provided by CD Limited. The technology generated a geographically referenced bathymetric dataset within the footprint of the restricted access areas. Post-processing of the data allowed us to generate a complete bathymetric data model of each berth that was referenced to the horizontal and vertical datums of the project.

The use of an ROV to perform this hydrographic survey proved to be an effective solution to collecting accurate bathymetric data and managing risk for planned future operations at the site. Other survey options suffered from a lack of data density, poor positional accuracy, or incomplete coverage of the berth floor.

Our solution affords the opportunity to collect hydrographic survey data that is comparable in accuracy and density to a traditional vessel-based hydrographic survey dataset so long as standards such as horizontal accuracy control, vertical measurement control, and vertical datum control are maintained throughout the survey operations. When the stakes are high enough and complete data is necessary to support the design, construction, or operations at a site with restricted access conditions, this solution can generate a valuable data set that outperforms diver-based or vessel-based surveys in terms of accuracy, density, and/or coverage.

As a footnote to this discussion: This project was completed for NISMO in April 2006. In early November 2006, the Intrepid Sea, Air, and Space Museum attempted to move the decommissioned aircraft carrier *USS Intrepid* from her mooring at a pier on the west side of Manhattan, New York City. With VIPs and dignitaries in attendance, the towing contractor cast off all lines and began to pull the *Intrepid* from her mooring position alongside Pier 86 en route to a planned overhaul period at a shipyard in Bayonne, NJ. After moving 10 to 15 feet from the pier, the *Intrepid* grounded. *Intrepid* was placed back into her mooring and dredging was necessary around the carrier in order to free her hull from the mud. One month later (at the next full moon high tide) another attempt was made, successfully, to move *Intrepid* from her mooring and tow her to a yard in Bayonne where she would go through a complete refurbishment. To our knowledge, the Museum made no attempt to use an ROV fitted with an inertial navigation system to survey under and around the carrier prior to either towing attempt.

REFERENCES

[1] U.S. Army Corps of Engineers. “Hydrographic Surveying”. Engineering Manual EM 1100-2-1003. April 2004.