# Precise Navigation: Creating a "Sandbox" in the Port of Los Angeles and Long Beach, California

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## Introduction

The Port of Long Beach, California, began a project in 2012 to develop an Under Keel Clearance (UKC) system using the software PROTIDE (PRObabilistic TIdal window DEtermination) developed by Charta Software in the Netherlands. This system is intended to support the safe and efficient transport of Ultra Large Crude Carriers (ULCC) in and out of the port. National Oceanic and Atmospheric Administration (NOAA) has been supporting this project with high-resolution hydrographic surveys, wave buoys, water levels, and the development of a new Nearshore Wave Prediction System (NWPS). While the port's project only entails the build-out of the PROTIDE computation system, NOAA is using this project to pursue a larger objective of creating a suite of harmonized data that can be used by mariners in support of precise navigation and decision support.

**Keywords:** ENC, Electronic Navigational Charts, IENC, Bathymetry

## Precise Navigation

"Precise Navigation" conjures different meanings to different readers, so first let's define what this means in the context of this paper: Precise Navigation is the ability to navigate in four dimensions (X,Y,Z, and Time) with an accuracy statistically less than the uncertainties affecting the vessel's position – simple enough. But how do we do that? A vessel's horizontal positioning is fairly straight forward given today's GPS technology. However, for today's ships, the closest danger is, frequently, directly under the keel. This can be particularly problematic since a vessel's vertical position is typically the hardest to quantify. For instance, there must be accurate water levels, dynamic draft (the change in the vertical position of the vessel in the water with a change in forward velocity), loading, water density, and sea state to name the largest constituents. All of these characteristics are typically computed once, prior to entering a port or at strategic junctures where depth may be limiting. However, these parameters are not captured and provided to the mariner in a real-time sense so that it can be employed to make continuous navigational decisions. In order to do this, a system of sensors and data must be provided to feed the more complex computations needed to provide this level of accuracy. The International Maritime Organization (IMO) has termed this "eNavigation," which it defines as "the harmonized collection, integration, exchange, presentation, and analysis of maritime information onboard and ashore by electronic means to enhance berth-to-berth navigation and related services, for safety and security at sea and protection of the marine environment." (IMO, 2008) The underpinning standard to eNavigation is International Hydrographic Organization's (IHO) S-100 format. The S-100 suite of data standards seeks to harmonize all the various data types to better enable a highly integrated solution. However, to enhance the safety of a vessel from berth to berth may demand different data or inputs for each port, or even for different legs of a single passage. For instance, in the Port of Long Beach, California, the primary danger would be an ultra large crude carrier impacting the seafloor due to the open ocean swell conditions found during its approach to the pier. In Charleston, South Carolina, it might be currents running alongshore combined with speed restrictions due to Right Whales spotted in the area that causes severe crabbing angles, thus reducing the across-channel maneuvering room with other vessels. Whatever the navigational situation, the mariner needs the necessary information synthesized into an intuitive decision support system that allows them to navigate safely and maintain a diminishingly low probability of grounding, collision, or any other unfortunate outcome. So, within the context of eNavigation, NOAA's focus is on providing accurate and timely environmental intelligence to the maritime community and delivering that data to the location where the decisions need to be made.

Why is precise navigation needed? It is needed because the size of the ships are outsizing our waterways. Ultra Large Crude Carriers entering Long Beach, California, carrying more than a million gallons of crude oil are loading to drafts of 65 feet. Depending on the sea state in the approach channels, the ship's pitching may bring the hull dangerously close to the 76-foot channel floor. Alternately, Ultra Large Container Vessels with more 18,000 containers are entering New York with less than a foot of air draft above their mast as they pass under the Verrazano Bridge. Or, LNG Tankers are entering Lake Charles, Louisiana, with less than a foot under their keel as they pass through fragile salt water marshes. These challenges are being felt in ports across the world and will only get worse as the ships continue to get bigger and the funds for dredging the channels become even more scarce.

In order for captains, pilots, and their shore-side logistical support to properly plan and execute these passages given the tight safety margins, they will need a significantly richer set of data to help inform their decisions on timing the transits and the loading of cargo. This data includes up-to-date high-resolution bathymetry; accurate modeled water level data (both nowcast and forecast); wind, wave, and current fields; air temperature; visibility; precipitation; salinity; and air gap measurements for bridge clearances. All of these various pieces of data are currently available. However, they are in disparate locations and not all are available in data formats that can be readily ingested into existing shipboard navigation systems. In order to realize the vision described by the IMO's eNavigation initiative, NOAA is working closely with industry leaders in the Electronic Chart System (ECS), Portable Pilot Unit (PPU), and Electronic Chart Display and Information Systems (ECDIS) sectors to gather input on formats and delivery mechanisms that will best supply this data to the mariner. These efforts are currently being focused on the Port of Long Beach where a UKC system is being developed. This project seeks to turn these various pieces of meteorological and oceanographic data into intelligence by harmonizing and standardizing data formats and making them available so that they might be displayed in an intuitive fashion. Each of these key contributors will be discussed in detail below.

**Low Under Keel Clearance**

Many think of UKC only in terms of the depth of the seafloor and the static draft of the vessel transiting above it. However, from a mariner's perspective, this must necessarily take into play many other elements. Water level is the most obvious and important contributor to this equation. The term "tide" is frequently used to describe this, but only captures the astronomic contribution of the rise and fall of the sea's surface, whereas water level takes into account weather effects and riverine runoff contributions. In addition to the water levels, the other factors that must be considered include meteorological conditions, the vessel's motion induced by the prevailing sea state, the static draft of the vessel, the variation in this draft due to the vessel's motion through the water (dynamic draft), and the chemical composition of the water the vessel is sailing in (primarily salinity).

**Water Levels**

Charted depths are relative to Mean Lower Low Water in the United States, or Lowest Astronomical Tide in other countries. While this assures that there should usually be more water available for navigation than is shown on the chart (except for negative tides), how much is of particular concern for vessels with low UKC. Planning the voyage by the tides in order to maximize both loading and efficiency are practices that have been employed as long as man has taken to the water in ships. But doing so with the precision necessary to make a probabilistic calculation requires a much more robust understanding of water levels.

In tidally controlled waterways, we must understand and account for the fact that the tide is not the same elevation everywhere. This creates a unique problem in that even if we are very accurately measuring water levels, unless that gauge is following our ship around, we really don't know what the water levels relative to chart datum are at our particular location. This brings the need for both spatial and temporal modeling into clear focus. We need a spatial water level model, or "nowcast," to tell us what the water level is at locations other than where we are observing. We also need temporal, or forecast models in the destination port to facilitate accurate vessel loading at the departure port and to facilitate long, tidally controlled transits to ensure that the anticipated water level will indeed be available at the time the ship arrives.

As discussed earlier, these models must take into account not only the astronomic factors affecting water levels, but also the meteorological and hydrological effects as well. In many wide, shallow embayments, it is not unusual for strong meteorological fronts to drive significant non tidal water level excursions from astronomical based predictions. For example, in February 2015, the Port of Baltimore saw a 4.5 foot non tidal water level fluctuation in 19 hours due to the passage of strong winter frontal system (Figure 1).

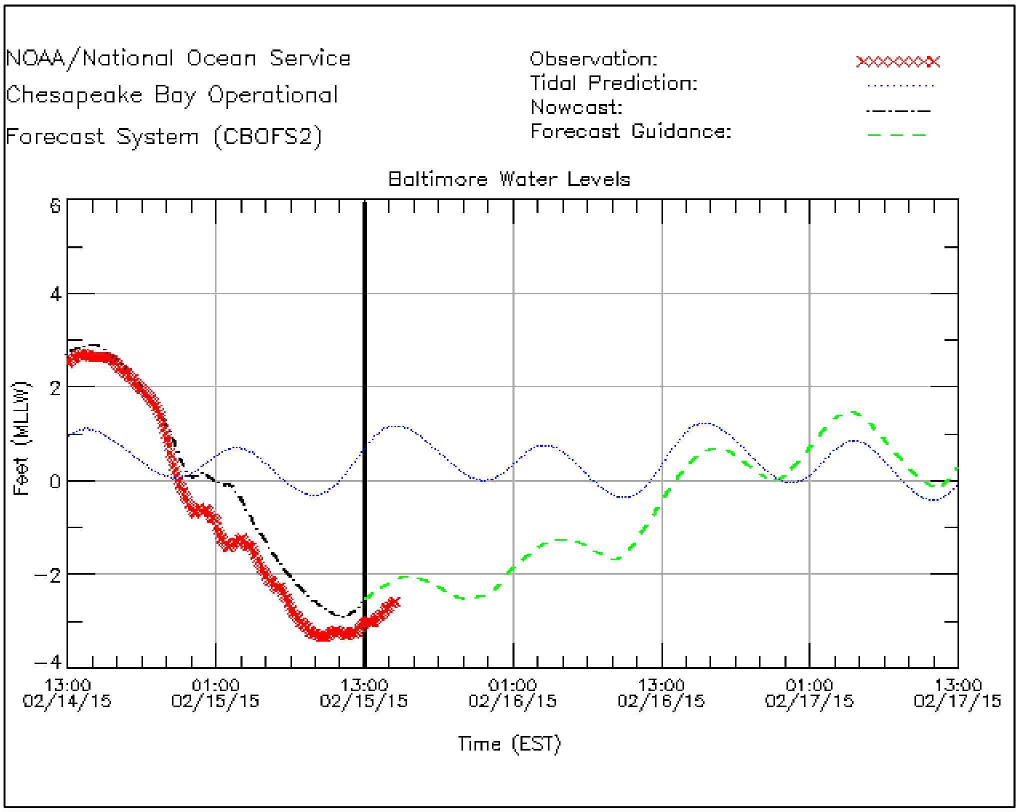


*Figure 1: Water Level fluctuations caused winter frontal passages – positive deviation caused by warm front with southerly winds preceeding a cold front a few hours later with strong NW winds*

Given the deeper drafts of modern ships, they are increasingly vulnerable to both tidal and non tidal currents with in constrained channels. This is especially a factor when ships are exposed to cross currents when turning broad side to main flow entering a pier or dock at slow speeds. Having high resolution nowcast and forecast current information is critical for these maneuvers given the high spatial variability of currents.

**Bathymetry**

The closer a vessel operates to the seafloor, the more we need to know about that seafloor. This means the depth measurements (soundings) need to be much more closely spaced (higher resolution), each measurement must have an associated uncertainty value, and some estimate of the geologic composition of the seafloor is also valuable.

Modern multibeam echosounders (MBES) and their associated positioning and orientation systems are capable of providing this information in great detail. While the hydrographic community at large has come a long way in quantifying the uncertainties associated with their sounding measurements, there is still much to be done. Real-time uncertainty estimates from all sensors in the survey suite (MBES, positioning, and orientation sensors) are still not broadly implemented by their respective manufacturers. Where these real-time uncertainties are being provided, surveyors are not universally using them to arrive at a total propagated uncertainty for each measurement in a survey. This is critical in order to inform an under keel clearance system about the uncertainty in the data at the time of the survey. The temporal uncertainty of the data, or how quickly a particular section of seafloor changes with time, is best managed locally where local knowledge is best. However, as the navigation community begins to rely on and demand higher accuracy data, it is not unreasonable to believe that the need for more periodic surveys will be required.

With this increase in resolution and accuracy must also come an evolution in nautical cartography. The current system of predetermined soundings, contours, and depth areas must give way to a more algorithmic cartography performed as a part of the display process that exploits this higher resolution data. With the advent of the International Hydrographic Organization's (IHO) new S-102 standard, there will be the opportunity to provide bathymetric data an order of magnitude greater than what is currently found on present-day charts. This opens the door for ECDIS to pick up some of the responsibility of the cartographer. For instance, the opportunity for a more robust sounding selection and rendering of depth areas are possible.

**Ship’s Motion**

Ship's masters have always intuitively understood the motion characteristics of their vessels, whether it is the vessel's dynamic draft or its heave, pitch, and roll characteristics. However, "when ships get too big for their ditches" (Gray, 2001), knowing these intuitively is not good enough; we must know them exactly. Each vessel that is compliant with the Safety Of Life At Sea (SOLAS) Convention and is operating in a low UKC environment needs to be instrumented with sensors that can provide actual data that supports and corroborates what is modeled during its design. This information can then be used to validate a UKC system upon its commissioning and provide valuable data toward the computation of the vessel's effective draft under different sea states, loading, and environmental conditions.

## Meteorological and Oceanographic Data

If ECDIS systems are to reach their full potential as "Information Systems" on the bridge of a ship, we must provide them with as much meteorological and oceanographic data as possible so that they may be used as the decision support tools for which they were intended. For meteorological data this includes wind, wave, visibility, and weather observations and forecasts, and for oceanographic data might include water levels, currents, salinity, and sea water temperature observations and forecasts. Once in the ECDIS system, this data can be used in calculations to estimate the increase of the vessel's effective draft due to an increase in the sea state, or how much lower a vessel will sit in the water due to a decrease in salinity as it moves up a river, or plan its route based on the latest weather forecast. All of these abilities move the ECDIS system from just a simple navigation tool to a more broadly capable geographic information system upon which the mariner also navigates.

Finding a reliable delivery system will be a challenge. However, most modern SOLAS-class vessels have the ability to connect to the internet for crew morale, to transmit fuel consumption information to their home office, to provide remote medical support, to enable anti-piracy capabilities such as surveillance cameras, and, finally, to support the access to advanced navigation information (Dale, 2014). This is a ready pipeline for getting environmental data into the ECDIS in an automated fashion and putting it at the fingertips of the mariner. But even in the absence of expensive satellite internet systems, anyone within reach of a 4G cellular network can easily connect to the internet. While internet access is not universal at sea, it is more ubiquitous now than it was just five years ago.

The key to broad acceptance will be the development of a flexible, light-weight, and extensible data format that will support the transmission of this data to the ship. Several formats are already in existence in the science community, most notably the General Regularly-distributed Information in Binary form (GRIB), Hierarchical Data Format (HDF), and Network Common Data Form (NetCDF) which also supports the HDF format. The IHO Surface Currents Working Group is developing this new format based on HDF. There are also similar efforts underway by other working groups within the World Meteorological Organization to support the dissemination of weather data.

**The Port of Los Angeles and Long Beach (LA/LB) Project**

The Port of Long Beach and the Port of Los Angeles are ranked sixth and eighth in tonnage in the United States respectively, moving a combined 139.2 million metric tons (USDOT, 2012). The channel leading into the Port of Long Beach has an authorized depth of 76 feet and local regulations allow drafts of 69 feet for ships with a displacement of up to 420,000 tons. In late 2012, at a Harbor Safety Committee meeting for these two ports, the Jacobsen Pilots noted that during storms and long period swell conditions outside of the breakwater, ULCC demonstrated significant levels of pitch in high wave situations. As a point of reference, a 1,000-foot vessel pitching just 1° will experience an increase in draft of more than 10 feet (Figure 2). As a result, the captain of the port froze the maximum draft at 65 feet until they understood the effects of the swells on the ULCC and could better predict their behavior.

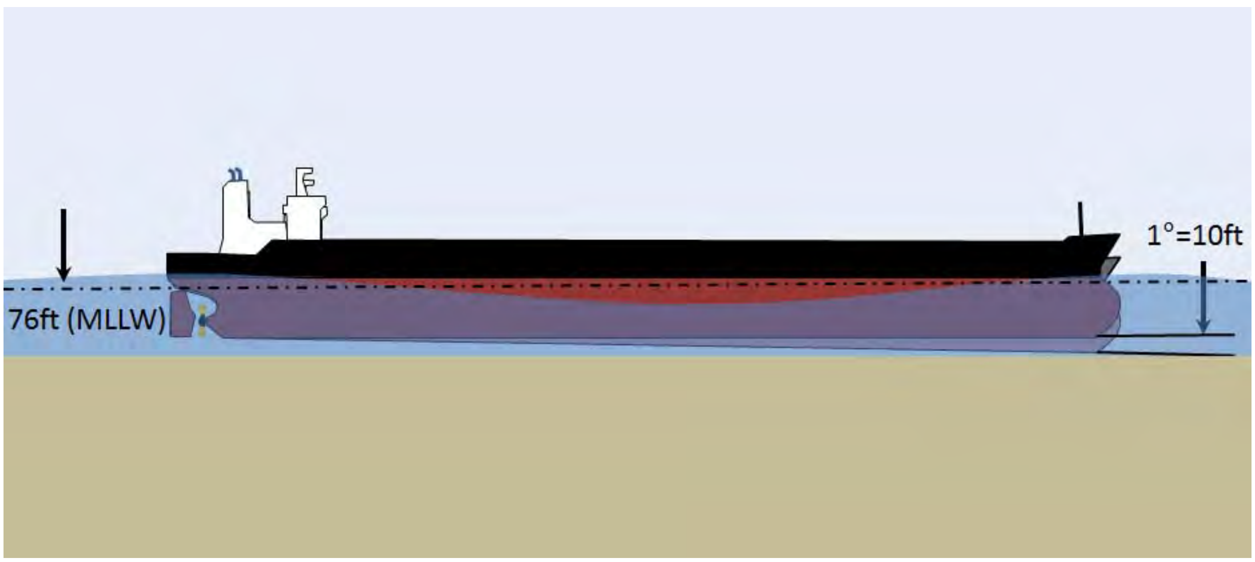


*Figure 2: How pitch can affect draft and safe clearance.*

The effect of reducing the under keel clearance means that ULCC must wait outside of the sea buoy until conditions are favorable to make the transit into port, or lighter to another vessel in order to reduce their draft; both are expensive delays. As a result, the Jacobsen Pilot Service (JPS) created a partnership with the California Office of Spill Prevention and Response (OSPR), the Port of Long Beach (PoLB), Tesoro, and the Pier 121 users, and selected the Marine Exchange of Southern California as a neutral partner to serve as project manager and fiduciary agent in a contract with Charta Software (https://chartasoftware.com/Article/385) to develop an UKC system for PoLB using their software PROTIDE. NOAA is supporting this endeavor by providing new, high-resolution surveys, creating high-resolution bathymetric products including Inland ENC (IENC) and S-102-like overlays, and a number of standardized environmental observations and forecast products that are within its operational portfolio. While these products will benefit PoLB, they will be disseminated through normal operational channels and will be available freely and openly to all users. The intent is to spur the development of new tools to provide better decision support to mariners navigating with limited maneuvering tolerances (both horizontal and vertical).

### Wave Models

The National Weather Service (NWS) is in the process of developing the Near-shore Wave Prediction System (NWPS), a series of high-resolution wave models developed by the National Center for Environmental Predictions and designed to run locally in all coastal Weather Forecast Offices (WFOs). The NWPS will provide coastal zone forecast wave guidance to support such activities as maritime navigation and rip current forecasts. The model for the Ports of Los Angeles and Long Beach will have a resolution of 0.5 km and will forecast such sea state variables as the height and direction of waves and swells out to five days in the future (Figure 3). This information is planned to become available to the ports and the public experimentally starting in the summer of 2015 through WFO Los Angeles/Oxnard's website (http://www.weather.gov/losangeles) and regular NWS forecast dissemination pathways. A wave model by itself cannot predict vessel motion. However, when coupled with a ship's motion modeling algorithm the wave spectra and direction can determine the angular excitation a particular ship will experience at various headings. It is in just this way that this model will be used by PROTIDE to compute each vessel's effective draft.

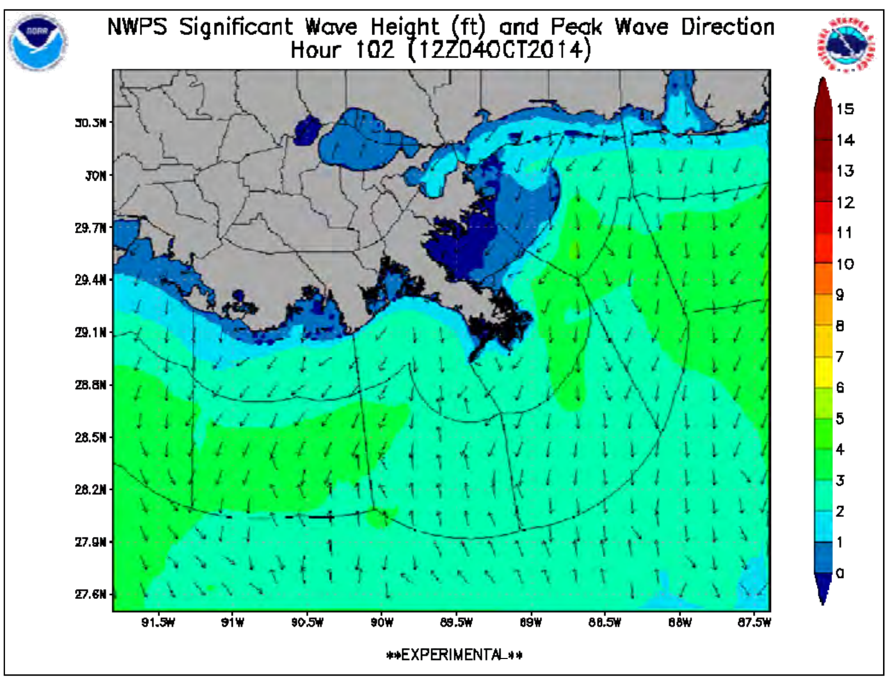


*Figure 3: Example of Nearshore Wave Forecast.*

**Wave Observations**

The U.S. Integrated Ocean Observing System has provided funding to deploy a wave buoy in collaboration with the U.S. Army Corps of Engineers and the California Department of Boating and Waterways. This buoy will join others in the Coastal Data Information Program (CDIP) network (http://cdip.ucsd.edu/). The program consists of an extensive network of buoys deployed along the coastal United States that provide near real-time information on wave height, period, and direction. This information is critical for a wide variety of users ranging from harbor masters, mariners, recreational boaters, and surfers. This wave buoy was deployed in October 2014 in the southern shipping separation zone of San Pedro Bay (Figure 4). Data from this buoy is available through the CDIP website (http://cdip.ucsd.edu/), the Physical Oceanographic Real-Time System (PORTS®) website (http://tidesandcurrents.noaa.gov/ports/index.html), and the NWS National Buoy Data Center website (http://www.ndbc.noaa.gov/). Data from this buoy will be used to validate the skill of the NWPS model.


*Figure 4: Example of CDIP wave buoy being deployed.*

**PORTS**

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) is responsible for developing and disseminating physical oceanographic data and products for the United States. These products provide both near real-time information on the water levels within the ports and tidal predictions of water levels and currents. The Mean Range of Tide at the Los Angeles tide station (9410660) is 1.16 meters and hence a critical factor in the computation of under keel clearance. The PROTIDE software will use both astronomical tide predictions and observations from this tide station for its computations. Tidal current predictions based on a current meter that had been installed (and since removed) near the main shipping channel near Queens Gate will also be used by the system. These products are available through the CO-OPS website (http://tidesandcurrents.noaa.gov/).

**Hydrographic Surveys**

From August 13 to November 11, 2013, the NOAA Ship *Fairweather* conducted multibeam surveys of the Ports of Los Angeles and Long Beach (Figure 5). Project OPR-L318-FA-13 was broken into four surveys (H12617, H12617, H12617, and H12620) that covered approximately 61 square nautical miles. The majority of the survey area was previously charted with piecemeal data of various vintages, sources, and coverage types (Figure 6). The most recent Office of Coast Survey (OCS) project prior to this one, OPR-L325-KR-00, was conducted offshore of the breakwater in 2000. Therefore, this project enabled NOAA to create a seamless baseline of high resolution from which to develop a gridded bathymetric database. This database will be the foundation from which to develop all future products.

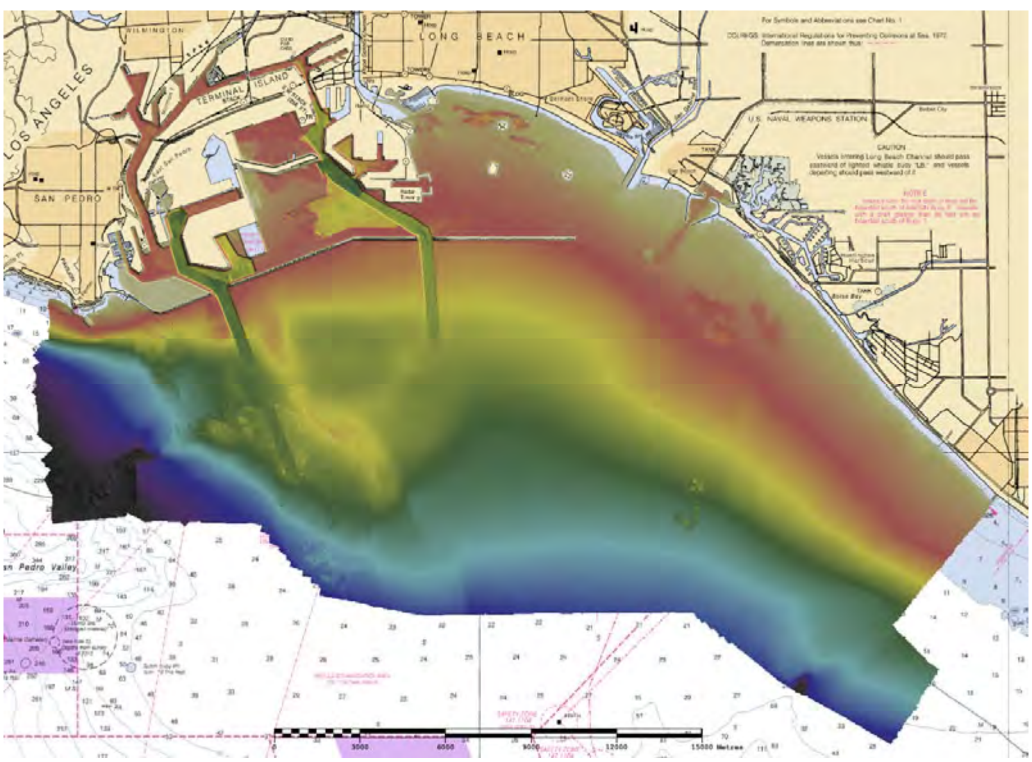


*Figure 5: Multibeam Survey coverage for OCS project OPR-L318-FA-13.*

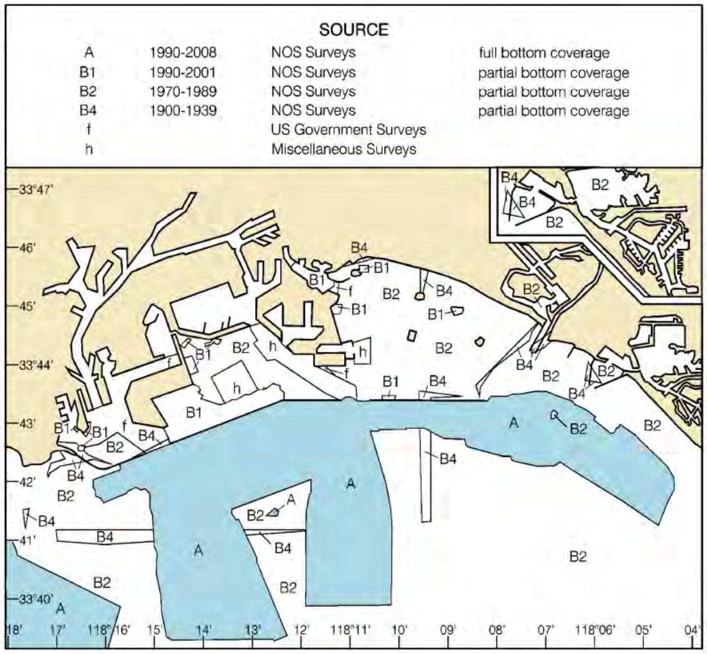


*Figure 6: Chart (18746) Source Diagram showing previous survey coverage.*

## Electronic Chart Formats

The concept of high-resolution bathymetric products is not a new one. The European Union funded a project called Effective Operations in Ports (EFFORTS) to help optimize port operations for the Port of Hamburg and the Port of Rotterdam. One of the project deliverables was the Port ECDIS that combined a Port ENC containing detailed topographic features at a large scale with high-resolution bathymetry. This project utilized both the Bathymetric Attributed Grid (BAG) format developed by the Open Navigation Surface Working Group and the bENC format developed by SevenCs (Seefeldt, 2010).

After some consideration, NOAA decided to use internationally accepted standards where possible for ease of product development and to encourage software vendors to test our prototype products. A variant of the ENC designed specifically for use in inland waters that allows for high resolution vector bathymetric overlays has been created by the Inland ENC Harmonization Group. This same format is being used by our partner agency, the United States Army Corps of Engineers, for prototyping bathymetric overlays in Southwest Pass at the terminus of the Mississippi River and presented a logical choice. This format allows overlays of high-density soundings and contours, but does not permit depth areas.

NOAA is also eager to use this project as an opportunity to test the new S-102 format for bathymetric surfaces. A draft version of this product specification was released for review in 2012; however, its basic format followed that of the Bathymetric Attributed Grid, which is optimized as a data transfer standard, but initial tests showed that further development was needed for its use in ECDIS systems. The IHO S-100 working group that is in charge of developing this standard met in early 2015 and is expected to release an improved and updated standard by late 2015 that should address these implementation issues. Once released, NOAA will work with its partners to implement this specification into software and begin testing prototypes as soon as possible.

### Creating a prototype IENC

For testing purposes, a smaller section of survey H12617 was chosen to create a prototype IENC. This area was further broken down into tiles to help manage file size, similar to that employed by the Canadian Hydrographic Service (CHS) in their S-102 project on the St. Lawrence River (Journault et al, 2012). Using the CHS three-level scheme of chart scales (Harbour, Coastal, and Overview), a small set of tiles were manually created at the Harbor level (0.02° x 0.02° cells) with an origin at (33N, 118W) using Caris BASE Editor. Two cells were then selected for the test area, one outside and one inside of the breakwater (Figure 7).

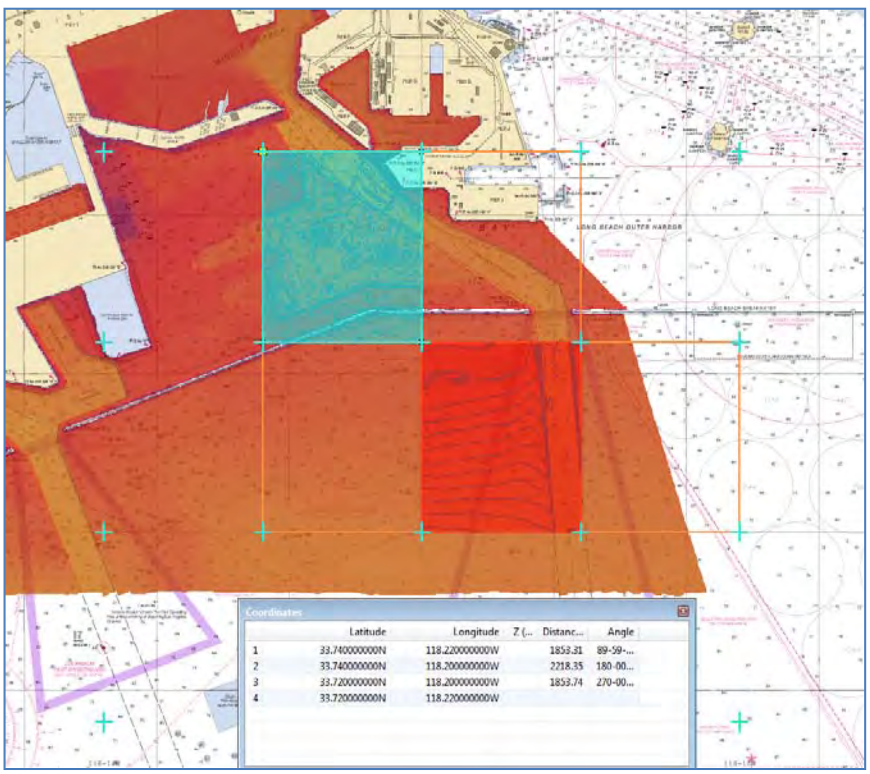


*Figure 7: Tiling scheme with IENC test cells highlighted.*

Contours were generated at intervals ranging from every decimeter to every two meters. Soundings were also generated at a number of intervals ranging from a five-meter radius selection to a twenty-five-meter radius selection (Figure 8 & 9). These groups of contours and soundings were then brought into Caris S-57 Composer to generate IENC products using the U.S. IENC v 2.1 profile customized to include a waterway code of 'SPB' for San Pedro Bay, the broader area that encompasses both the ports of Los Angeles and Long Beach. These products were then tested for readability in Orca Pilot v 4.5.2, SEAiq, and Coastal Explorer software packages. After reviewing the various combinations of contour and sounding density, it was decided that the final IENC product should include 5-decimeter spaced contours and group soundings at a 25-meter radius, thus keeping the final product under the 5MB size limit for IENCs.

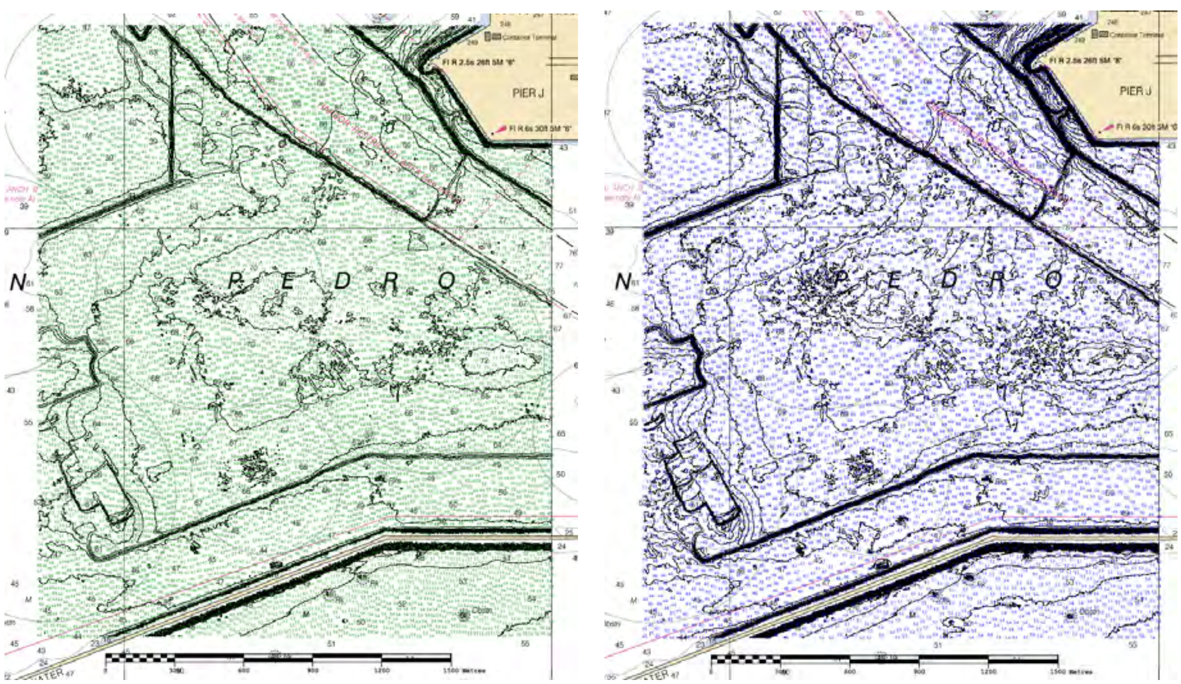


*Figure 8: Comparison between soundings spaced at 20m radius and 1m contours vs 25m radius sounding spacing and half-meter contour interval.*

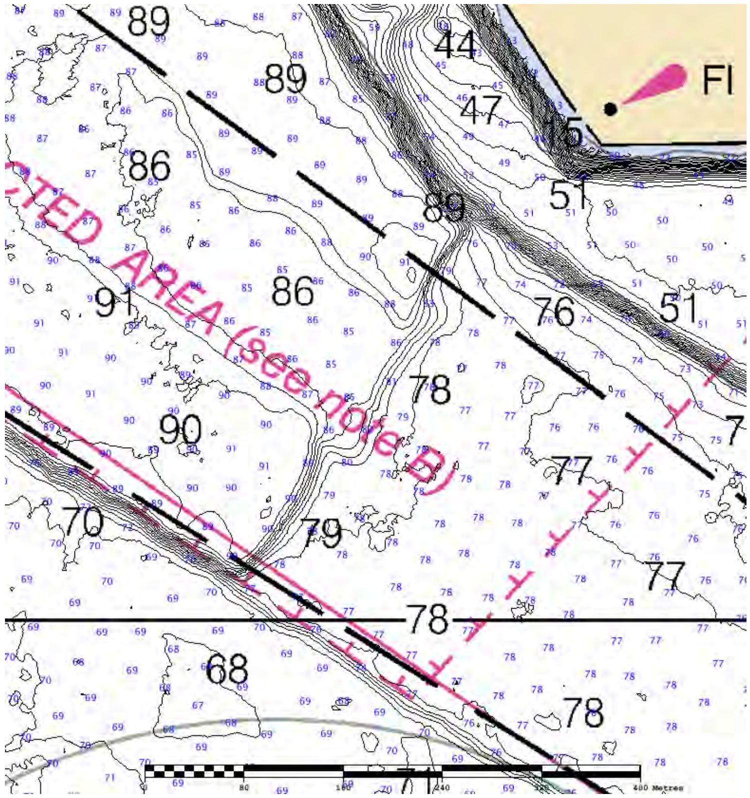


*Figure 9: Close-up of the final overlay density of 25m radius sounding selection and half-meter contour interval.*

**LA/LB Test Bed**

The Office of Coast Survey is currently working with several ECS and PPU manufacturers as well as the Jacobsen Pilot Service as they evaluate these products. Because this data is not intended for use in an ECDIS and is unconstrained by the S-52 display standard, it is hoped that these manufacturers can pursue new and innovative ways to use and portray this data. This data is also being used in a web-based tool that applies real-time water levels to the gridded bathymetry and allows the user to define their effective draft. Software on the server then colors the data on the chart to show the location of safe water based on this draft input. All of these products are intended to both encourage industry to lean forward into this new technology, as well as provide a vehicle to engage and educate the mariner about the possibilities of high-resolution data fusion in the context of precise navigation. The Office of Coast Survey is only at the beginning of this project, but has already received encouraging feedback from industry and has committed to keeping this project operational for the next five years. During this time, we intend to use this project to inform us on maintaining an operational gridded bathymetric database and use that database to further innovate the tools and products that we provide to mariners.

## Conclusion

The increased size of vessels entering U.S. ports, coupled with the diminishing margins that they must navigate with reference to the seafloor has provided an opportunity for NOAA to develop new products to support these vessel's need for precision navigation. The PoLB will serve as the testing ground for this development and allow us to examine their value to the mariner under actual, at sea conditions.

While Coast Survey is primarily focused on navigational charts, it is also working with its partners throughout the agency to bring all NOAA data to the mariner where it's needed most-the bridge of their ship. We are doing this through expanded partnerships with our commercial partners in both the ECS and ECDIS industry as well as app developers for mobile devices to deliver this data in a unified and intuitive fashion that requires minimal intervention from the mariner.

This project also provides an opportunity to educate the mariner about the possibilities the various NOAA data hold for navigation and to demonstrate how the whole is greater than the sum of its parts. For instance, high resolution bathymetry is useful, but when it can be paired with both real-time and forecast water-levels the combination is a much stronger decision support tool than either product used independently. Carrying this thought to its logical conclusion would mean the mariner would have all these streams of data at their disposal for use in whatever navigational situation they may find themselves, whether it's a high current situation, or planning a passage, or laying out the approach to anchorage. All these data can be brought to bear in order to allow the mariner to make the best decision possible. And, that is the ultimate goal we are trying to achieve.

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