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MODERN UNDER-KEEL CLEARANCE MANAGEMENT

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Abstract

This paper provides an overview of recent technological developments that have improved the ability to manage under-keel clearance (UKC) in ports. The inaccurate determination of the UKC of large-draft ships entering or leaving depth-limited ports can have serious safety, economic, and environmental consequences. A ship's master can manage his ship's UKC by: (1) taking actions that affect the ship's dynamic draft (such as changing the ship's speed) and (2) scheduling his ship's transit of the planned route to ensure that there will be sufficient water level for safe passage when the ship reaches locations with controlling depths. To do this, however, he must have accurate real-time and forecast environmental information along his route, as well as a validated method of predicting his ship's motion (and thus dynamic draft) for various situations. At a minimum, this information must include accurate charted depths and underwater hazards, water levels, and ship-specific channel-specific prediction formulas for dynamic draft (based on ship speed, static draft, and water depth). The dynamic draft calculation may also require information on currents, water density, and waves, swell, and/or seiching. Recently developed systems that can provide the necessary information for UKC management include: nowcast/forecast oceanographic model systems (a necessary step beyond real-time oceanographic systems); on-the-fly GPS systems to provide accurate ship motion data for calibrating dynamic-draft prediction systems; modern hydrographic measurement systems (such as shallow-water multibeam and side-scan sonar systems); and modern electronic nautical chart systems (and their supporting rapid update services). This paper includes discussion of what further improvements to these systems are needed to make effective UKC management a reality.

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INTRODUCTION

The determination of under-keel clearance (UKC) became a critical factor in safe and efficient navigation when modern vessels became so large that they could not enter major ports except near times of high water. Because inaccurate determination of UKC can have serious safety and/or economic consequences, many ports provide *guidelines for minimum under-keel clearance* in their navigation channels. These guidelines essentially provide a safety margin that reflects their best judgment on present capabilities to determine UKC in these waterways. They can be based on such things as how recently charted depths have been updated by surveys, or how much the wind might cause the water level to be lower than the predicted tide. If such guidelines specify a minimum UKC that is too large, then the result may be economic losses due to less cargo being carried, unnecessary lightering, or unnecessary delay while waiting outside the entrance for higher water. If such guidelines allow a minimum UKC that is too small, then groundings may occur, which could have economic consequences if the grounding closes the port or leads to property damage, as well as environmental consequences if a hazardous spill results. (When a ship has too little UKC it loses maneuverability, so a collision is also possible.)

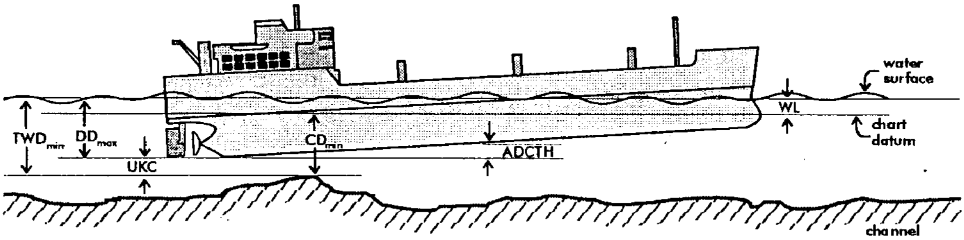
Many shipping companies have policies dictating a passage planning requirement that includes estimation of UKC along a ship's entire route. The U.S. Coast Guard recently issued a regulation (U.S. Coast Guard, 1997) making this a requirement for all single hull tankships. Tankship owners or operators are required to provide ship's masters with written UKC guidance. Prior to transiting to or from port the tankship master must plan the ship's passage using that guidance, must estimate the anticipated UKC, and must discuss the plan and UKC with the pilot. Items to be addressed in that plan include vessel draft, controlling depth of the port, the impact of weather and other environmental conditions, and ship's speed and squat.

It is difficult to predict when the economy-of-scale benefits that have led to the increasing size and draft of bulk carriers, container ships and oil tankers will finally reach some limit. It may be that the primary prohibitive factor will be the lack of funding for most ports to dredge channels deep enough to accommodate larger ships. But, short of the unlikely possibility that ports will find the funds to dredge channels much deeper than the largest-draft vessels, the accurate determination of UKC will play a critical role in the safety and economic life of all ports.

The more accurately that UKC can be determined along the entire route of a ship coming into or leaving port, the more cargo that can be transported and the more safely that transport can take place. Technological advances in telecommunications, computer power, measurement sensors (including satellites), GPS, and oceanographic, meteorological, and ship-motion computer models are improving our ability to accurately estimate UKC. Many ports will soon have the real-time and forecast information and supporting vessel response analyses needed for effective *under-keel clearance management* (UKCM). The purpose of this paper is to provide an overview of where this modern technology has brought us with respect to UKCM, and what steps are required to make effective UKCM a reality. (It is not meant as a review of all work done in these areas, although examples will be given where needed to illustrate a point.)

THE ELEMENTS OF UNDER-KEEL CLEARANCE

Under-keel clearance (UKC) is the term commonly used to define the distance between the lowest point on the ship's keel (or hull) and the highest point on the channel bottom beneath the ship. UKC has two main components, and is the difference between them. UKC is equal to the minimum *total water depth* at the location of the ship minus the maximum *dynamic draft of the ship*. The dynamic draft is the distance from the water's surface to the lowest point on the ship's keel while the ship is in motion. Each of these components has several elements (see Figure 1).



$$\text{UKC} = \textbf{Minimum Total Water Depth} - \textbf{Maximum Dynamic Draft}$$

$$\text{UKC} = \text{TWD}_{min} - \text{DD}_{max}$$

$$\text{UKC} = \left\{\begin{pmatrix}\text{Minimum}\\ \textbf{Charted Depth}\\ \\ \end{pmatrix} + \begin{pmatrix}\textbf{Water Level}\\ \text{above chart datum}\\ \text{(astronomical tide}\\ \text{+ wind-induced)}\end{pmatrix}\right\} - \left\{\begin{pmatrix}\textbf{Static Draft}\\ \text{(due to cargo}\\ \text{and water}\\ \text{density)}\end{pmatrix} + \begin{pmatrix}\textbf{Sinkage}\\ \text{(due to}\\ \text{ship's}\\ \text{speed)}\end{pmatrix} + \begin{pmatrix}\textbf{Additional Draft}\text{ from}\\ \textbf{Change in Trim and/or Heel}\\ \text{(due to ship's speed and/or}\\ \text{turning and/or wave effects)}\end{pmatrix}\right\}$$

$$\text{UKC} = \{\text{CD}_{min} + \text{WL}\} - \{\text{SD} + \text{S} + \text{ADCTH}\}$$

FIG 1.- Elements of under-keel clearance.

The total water depth consists of the *charted depth* plus the *water level* above the chart datum. The charted depth is the distance from the chart datum (a tidal low-water datum, such as mean lower low water, MLLW) down to the channel bottom. The charted depth can be a controlling depth for a channel or an individual depth. There are always uncertainties associated with charted depths. For example, not all underwater obstructions (especially small ones) may be shown on a chart. The exact position of the bottom, if it is made of layers of mud, may not be known exactly. For older depth measurements, lead lines may have sunk a certain distance into the mud, which may or may not be the same as the distance of acoustic penetration in modern depth measurement systems (depending on the acoustic frequency). There are uncertainties associated with each depth measurement technique and with tidal correction of the measured depths.

The water level above (and sometimes below) chart datum varies with time, often significantly over time periods as short as a few hours. There are many phenomena that affect the water level and how it varies with time. In most ports water level variation is usually dominated by the *astronomical tide*, and the mariner has generally relied on published Tide Tables for the best available prediction of water level at any given time. However, water level can also be affected significantly by meteorological phenomena, especially the *wind*, but also by atmospheric pressure, river discharge, and water temperature. None of these can be included in Tide Table predictions. Wind effects are most pronounced for ports that are part of a large shallow bay and/or border on a wide shallow continental shelf. In some locations (such as parts of the Gulf of Mexico) the wind effects often dominate the tide (even when there is not a hurricane or major storm). Even for locations where the tide dominates, it does not take much wind to affect UKC enough to have a serious economic or safety consequence if it is not considered. Wind effects can change as quickly as the tide if a weather system moves through the area fairly quickly. Changes in water level due to the other meteorological effects are generally slower. Changes in water temperature, for example, are seasonal. In the summer the water is warmer and thus less dense, so there is an expansion of the water column and a small but significant increase in water level.

The dynamic draft also has a number of elements. The *static draft* is the draft of the ship when it is not moving; it is primarily affected by how much cargo is loaded (and where it is placed in the ship). If the cargo is not loaded symmetrically it can affect the ship's *trim* (i.e., the stern-to-bow angle of the ship relative to the horizontal) and/or its *list* (i.e., the ship's port-to-starboard angle relative to the horizontal). The static draft can also be affected by *water density*, being greater in fresher water where the ship has less buoyancy. Once the ship is in motion, there are a number of other effects on the ship's draft. The BERNOULLI effect (less pressure when a fluid moves faster) causes a ship in motion to sink lower in the water (referred to as *sinkage* or *settlement*) and to change its trim (sometimes referred to as *squat*, but the term squat is often used to represent both the sinkage and the change in trim, and it will be used that way in this paper). The BERNOULLI effect on the ship is very dramatic in shallow water. When a ship makes a turn the ship's port-to-starboard angle (referred to in this context as *heel*) will change. When any of these effects changes the lowest point of the ship's keel in the water, then the effective draft is changed. Currents will also affect the dynamic draft of the ship, contributing to or reducing the above effects. All of these dynamic effects on draft depend on the design of the vessel, its static draft, the depth of the water, the speed of the vessel, and the speed and direction of the currents. Another effect on dynamic draft is caused by *waves and swell*. These are short-period oscillatory changes in water level, with wavelengths generally shorter than the length of the ship. The lowest point in the water that any part of the ship's hull reaches contributes to the maximum draft. The *heave* (vertical up and down motion of the entire hull), the *pitch* (the angular up and down motion of the bow and stern in opposite directions), and the *roll* (the angular up and down motion of the port and starboard sides of the ship in opposite directions) all can contribute to the maximum draft.

MANAGING UNDER-KEEL CLEARANCE

There are a number of ways that a ship's master can effectively manage the UKC of his ship. These fall into two categories: (1) those actions he can take that affect his ship's dynamic draft, such as changing the speed of his ship; and (2) those (planning) actions that will ensure that there will be sufficient water level for safe passage when he reaches locations with controlling depths along his route. Both are dependent on having the necessary real-time and forecast environmental information and supporting analyses of his ship's motion in varying situations. Both types of actions will have economic consequences that he will consider when making his decisions.

A ship's master can always increase UKC by slowing his ship. This action will have economic repercussions (e.g., arriving later at the pier), so he must have the necessary information to determine exactly how much he will have to slow down to avoid grounding (or to stay within the port's minimum UKC guidelines). If there is a real-time water level system in that port, as well as accurate nautical charts, he will have up-to-date accurate information about the total available water depth. The critical information then is how much his desired ship speed will add to his ship's draft at the locations with controlling depths. If his dynamic draft will be too large, he must have accurate vessel response formulas telling him how much he must slow down. These formulas should be for his *specific ship* in those *specific channels* for the *same water level conditions* that he will soon face.

A ship's master can also plan to have his ship arrive at locations with controlling depths at times when there will be sufficient water depth for safe passage. This planning requires accurate forecasts of water levels at all locations along his route. Then, if he is bringing a ship into port, he can plan the ship's arrival at the entrance to the port (or at the bay entrance leading to the port) to coincide with a high enough water level to safely enter. Or, he can plan for the ship to safely pass a location with controlling depth further up the bay on the way to a port. If he is leaving port, such forecast water level information will tell him the best time to safely leave the port and bay. It will also tell the shipper how much cargo he can safely load. If the port does not have a forecast system (and most do not yet have them), the ship's master must rely on Tide Tables, always understanding that there will be a large uncertainty due to wind and other meteorological effects. (If the port has a real-time data system, the real-time water levels will generally not be applicable more than a couple hours into the future.) In order for the ship's master to be able to accurately manage his ship's UKC, he must, at a minimum, know the ship's static draft and have accurate information along his route on:

(1) charted depths and underwater hazards;
(2) water levels (real-time and forecast out to 24 hours into the future, as well as tide predictions); and
(3) channel-specific ship-specific formulas for dynamic draft (based on ship speed, static draft, and water depth).
(4) The dynamic draft calculation may also require information (from the present to 24 hours into the future) on:
(5) currents, where they are large enough to have an effect ;

(6) water density, for ports where river discharge can be significant; and
(7) waves, swell, and/or seiching, for ports on the open coast.

The provision of the above information for UKCM will depend on systems that make use of recent technological advances in telecommunications, measurement sensors (including satellites), GPS, oceanographic, meteorological, and ship-motion computer models, GIS's, and computer power. These systems include:

(a) modern electronic nautical chart systems and their supporting rapid update services [providing item (1) above];
(b) modern hydrographic measurement systems, such as shallow-water multibeam and high-speed high-resolution side-scan sonar systems [providing the data for item (a)];
(c) real-time oceanographic systems [providing real-time information for item (2) at selected locations, as well as for items (4)-(6) for some ports];
(d) nowcast/forecast oceanographic model systems [providing real-time information for items (2), (4), (5), and (6) at hundreds of locations where there are no sensors installed, as well as forecasts (out to 24 hours) for these same items];
(e) vessel response prediction (VRP) systems [providing item (3) above]; and
(f) on-the-fly (OTF) GPS systems [providing data on ship motion which, when combined with data from the above systems, can be used to validate VRP systems in item (e)].

In the next sections of this paper we look in some detail at these still developing systems that are beginning to make accurate UKCM a reality.

NOWCAST/FORECAST OCEANOGRAPHIC MODEL SYSTEMS

The Need For Real-Time and Forecast Water Levels

Modern UKCM depends on knowing the water level as accurately as possible at all points along a ship's route up to 24 hours into the future. For more than a century the mariner has relied on published national *Tide Tables* for the best available prediction of what the water level will be at any time. However, these Tables only provide predictions of the astronomical tide (and only at locations where tide gauges had been installed to obtain water level data). The important effect of wind on water level can not be included in such Tables, nor can the effects of atmospheric pressure, river discharge, or water temperature and salinity.

When ships became large enough that the wind-induced changes in water level became an important consideration that could not be ignored, *real-time water level measurement systems* began to be installed (APPELL *et al.*, 1994; PARKER, 1994; PRINCE, 1996; O'BRIEN, 1997; SILVER and DALZELL, 1997). Advances in telecommunications (satellites, the Internet, cellular phones, HF radio, etc.) allowed the user to have observed water level data within minutes of its measurement, instead of having to rely on astronomical tide predictions. This fulfilled the short-term needs of the mariner at a few locations considered most critical in each port. Using the real-time water level data, the pilot and the master on a ship approaching an area with a controlling depth could either: feel confident about safe passage beyond this point; take action to slow down the ship to reduce dynamic draft and increase UKC; or stop the ship if there will not be enough UKC no matter how much the ship is slowed.

Real-time water level measurement systems, however, do not provide information at locations where there are no water level gauges. And, more importantly, real-time systems do not provide water level information into the future, so that a ship's master can accurately schedule his ship's transit of the planned route, or so that a shipper can know how much cargo he can safely load.

The next step therefore was the development of *nowcast/forecast oceanographic model systems* driven by real-time data fields and forecast fields from weather models (PARKER, 1994; PARKER, 1998). Such model systems can provide:

(1) nowcast (i.e., real-time) water levels at hundreds of locations not instrumented with real-time water level gauges;
(2) forecast water levels up to 24 hours into to the future (to meet most mariner needs), and further into the future if necessary (with less accuracy);
(3) nowcasts and forecasts of other oceanographic parameters (in addition to water level) that may be needed in determining dynamic draft, such as currents, water density (from temperature and salinity), and waves/swell/seiches.

The nowcast and forecast current fields output by such model systems have high enough horizontal resolution to show current shears and eddies, which are important information for maneuvering a ship (another important aspect of navigation in addition to UKCM), and may also affect dynamic draft through their effect on ship motion.

Components of a Nowcast/Forecast Model System

A nowcast/forecast model system is very complex, involving not only the numerical hydrodynamic model of the port (or of the bay where the port is located), but also many sources of real-time oceanographic and meteorological data fields, as well as forecast fields from other oceanographic and atmospheric models (PARKER, 1998). For example, Figure 2 shows all the models that must provide forecast inputs to a model of Chesapeake Bay (where the Ports of Norfolk and Baltimore are located) in order to produce accurate water level forecasts throughout the Bay. Another example, given by PRINCE (1996), is the Port of Rotterdam water depth management system, which uses a one-dimensional hydrodynamic model driven by the forecast water levels from a North Sea model and the discharges of the rivers Rhine and Maas.

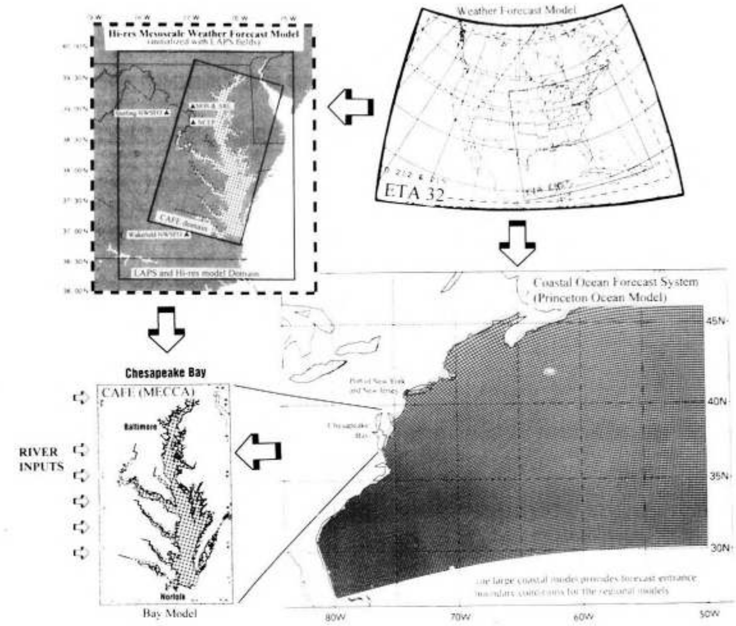


FIG 2-. Oceanographic and meteorological models required for a Chesapeake Bay nowcast/forecast model system. The Chesapeake Bay model (CAFE) presently has 5-km resolution. The weather forecast model is the National Weather Service's ETA 32, with 32-km resolution. The Local Analysis and Prediction System (LAPS) produces real-time 3-D meteorological fields from all available data to initialize the high-resolution weather forecast model over the Bay.

Figures 3a and 3b show the components needed for the Chesapeake Bay model system and the information transfer among them. Not all these components may be needed for a nowcast/forecast model system in another bay or port. Chesapeake Bay, being a very long shallow estuary, represents one of the most dynamically complex systems. Approximately half of the wind-induced changes in water level come from wind blowing over the Bay, and half from the wind blowing over the continental shelf, with the signal from the shelf propagating through the entrance and up the Bay. Forecast open boundary conditions at the Bay entrance must be provided by a *coastal ocean forecast model* for the entire East Coast of the United States (AIKMAN *et al.*, 1996). This coastal ocean forecast model must be driven with wind and other meteorological fields from a *large weather forecast model*. The forecast wind fields over the Bay itself must have high spatial resolution because of the Bay's complex geometry. Thus a *high-resolution weather forecast model over the Bay* must be run, with lateral boundary conditions provided by the same large weather forecast model that drives the coastal ocean forecast model. Also, a *system is needed to create real-time three-dimensional data fields* (from all available in situ and remotely sensed meteorological data over and around the Bay) to provide the initial conditions for the high-resolution atmospheric forecast model runs. This same system provides the wind and meteorological fields to drive the Chesapeake Bay oceanographic model when it is run in the nowcast (real-time) mode. The entrance water level forcing for the nowcast model runs can be real-time data from a water level gauge outside the entrance to the Bay. Real-time river discharges will also be needed to produce accurate nowcast salinities and water densities. Likewise, *river forecast models* are needed to provide the forecast discharges used to produce accurate forecast salinities and water

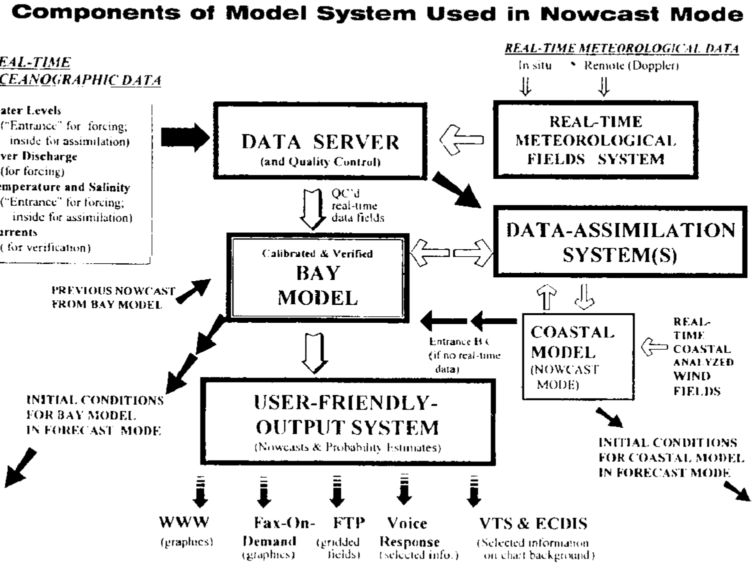


FIG 3a-. Components of a model system used to produce nowcasts of water levels, currents, and other oceanographic parameters. The arrows show the flow of data and information.

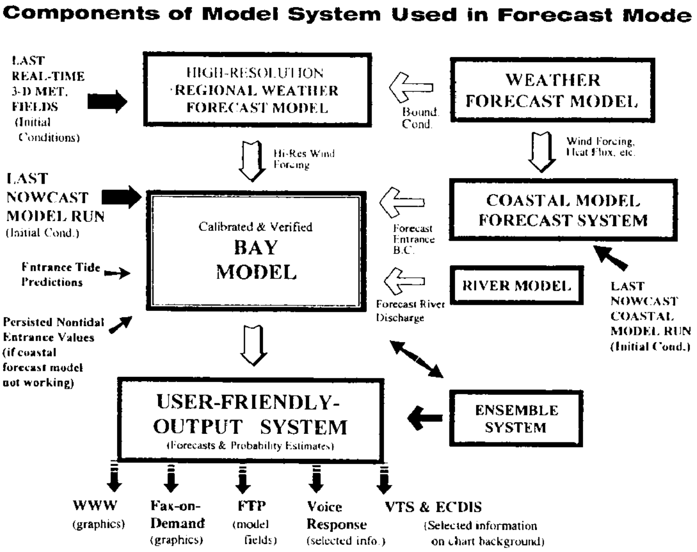


FIG 3b-. Components of a model system used to produce forecasts of water levels, currents, and other oceanographic parameters. The arrows show the flow of data and information.

densities. However, in estuaries where the river discharge can be very large, there will also be a direct effect on water levels and currents.

The complexity of implementing the components of a nowcast/forecast model system no longer presents major problems because of recent improvements in telecommunications, measurement sensors and real-time delivery systems, computer power, weather forecast models, and oceanographic models, as well as increasing sources of real-time data maintained by various agencies. The Coast Survey Development Laboratory (CSDL) in NOAA's National Ocean Service (NOS) is presently running (in a quasi-operational environment for testing) the Chesapeake Bay nowcast/forecast system depicted in Figure 2. One of the outputs provided on a (presently) restricted Webpage is shown in Figure 4. There are a variety of additional ways to disseminate the model predictions (some are indicated at the bottom of Figures 3a and 3b).

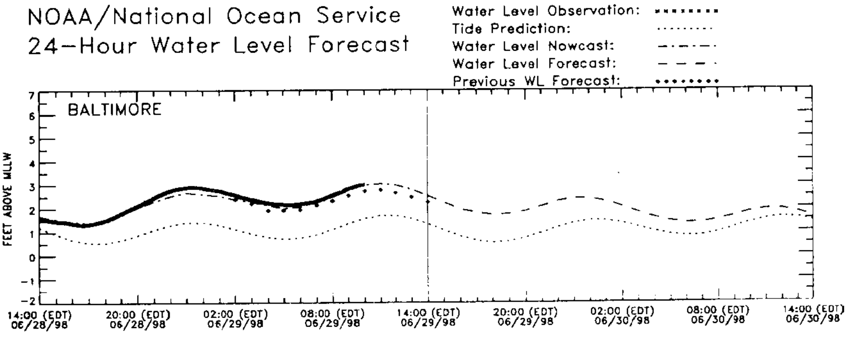


FIG 4.- Sample Webpage graphical output showing nowcast and forecast water levels at the port of Baltimore from the Chesapeake Bay model system.

All of the components shown in Figures 3a and 3b are needed for accurate nowcasts and forecasts in Chesapeake Bay (and most components are now operating). CSDL's nowcast/forecast system for the Port of New York and New Jersey (Port of NY/NJ) also requires forecast boundary conditions from the coastal ocean forecast model for the U.S. East Coast (see Figure 2), but does not need a high-resolution weather forecast model (nor the real-time meteorological fields system) over the harbor because the harbor is not large enough for the local winds to have much effect on the water level. Neither the Chesapeake nor New York model systems need the river inputs if water level prediction is the primary goal, but river discharge will become critical when those model systems begin to predict salinity and water density. A third model system in development at CSDL, for Galveston Bay and the ports of Houston and Galveston, does require river inputs for accurate water level and current predictions. The Galveston Bay model system also requires forecast water levels from a model of the Texas-Louisiana shelf, driven by forecast winds.

Nowcasts of water levels and currents from the Port of NY/NJ model system are presently updated hourly and provided on a Website. These nowcasts include detailed synoptic views of current fields on a chartlet, showing current shears and eddies, which are important to know for ship maneuvering and also can affect the dynamic draft portion of UKC. Forecasts from this and other model systems are less frequent, being tied to the cycle of weather model forecasts (presently twice a day, but soon four times a day). The nowcasts and forecasts from the Chesapeake Bay, Port of NY/NJ, and Galveston Bay model systems will be provided to the mariner through NOS's Physical Oceanographic Real-Time System (PORTS) (APPELL *et al.*, 1994; PARKER, 1994).

For some ports, usually those opening directly to the ocean and thus exposed to waves and swell, or those with the right dimensions for the waves or swell to cause seiching, some type of a wave forecast model system is required so that wave-induced effects on dynamic draft can be predicted (SILVER and DALZELL, 1997). Wave forecast models usually require real-time wave gauge data and good quality forecast wind fields from weather forecast models.

Improving the Prediction Skill of Nowcast/Forecast Model Systems

The primary issues remaining for nowcast/forecast model systems are issues dealing with maximizing their *prediction skill.* How accurately a particular model system can predict water levels and currents in real-time or in the future is obviously critical. If a pilot or ship's master uses a Tide Table, he knows its limitations (i.e., no wind effects are included) and is appropriately conservative in estimating the UKC of his ship. A nowcast/forecast model system, however, is supposed to give him an accurate prediction of the total water level, so that the master and/or pilot can calculate a more accurate estimate of UKC and thus not have to be as conservative. If, under some circumstances, the model system puts out nowcasts or forecasts that have errors, what will be the consequences? Such errors are more likely in a forecast than in a nowcast (since errors are more likely to be found in the various forecast inputs into the model than in the real-time data input), and such errors will probably be larger the further into the future one forecasts. Forecast errors would not likely cause accidents since as a ship got closer to a location with a controlling depth, the pilot or master would start using the real-time sensor data or the model nowcast information, both expected to be more reliable. Forecast errors, however, could have economic consequences, since the ship might be forced to wait for higher water, or perhaps slow up considerably to reduce dynamic draft and get behind schedule.

What is needed is an *uncertainty estimate* that accompanies (and is different for) each new forecast, to let the pilot or master know what the probability is that the forecast will be accurate. Developing methods to produce accurate uncertainty estimates for forecasts is presently the most difficult aspect of developing a nowcast/forecast model system. Eventually such estimates will probably come from some type of *ensemble averaging system* (similar to what is done in weather forecast model systems), where the model is run many times with different forcings to give a range of possible predictions. Hopefully the smaller the range between extremes the better the probability that the forecast will be correct.

Providing the pilot or master with the uncertainty of model-produced nowcasts is not a problem, since he will have real-time sensor data at a few locations to compare against model nowcasts and thus be able to see how well the model is doing. Such model-data comparisons (errors) at the few locations with water level gauges will be applicable to the rest of the port because water levels vary slowly over geographic distances. However, this is often not the case with currents, since they can change significantly in speed and direction over relatively short distances. Real-time current sensors, usually acoustic Doppler current profilers (ADCP's), therefore, will be put at locations with the fastest currents in areas most critical to safe navigation.

The skill of a nowcast/forecast model system depends first on having a well-designed (with correct physics), well-calibrated (with data) numerical hydrodynamic model that accurately reproduces observed data when it has proper data inputs. For skillful nowcasts to be produced by the model system, it must input accurate real-time data and data fields from the appropriate locations. For a small port (in geographic size), with its entrance directly leading to the continental shelf, real-time water level data from a gauge at (or even just inside) the entrance is the only requirement for skillful water level nowcasts throughout the port. A wind sensor or two will be sufficient for local wind, which only becomes a factor in the water level nowcast for very high wind speeds. For a port in a long shallow bay, an accurate nowcast can be more difficult to produce (than for a port in a small bay), since wind over the long shallow bay has a much greater effect on the water levels. A water level gauge at or inside the entrance of a large bay cannot be used to represent the nontidal wind-induced signal propagating in from the continental shelf, because its data will also include effects from the wind over the bay. Thus the real-time water level data must come from some distance outside the entrance to the bay. The large bay also requires real-time (analyzed) wind data fields over the bay, which must be produced from as many real-time wind sensors around and (especially) over the bay as needed to accurately represent the wind fields.

If there is a problem in either the real-time wind fields over the bay or the entrance water level forcing condition, the nowcast may be improved by using *data assimilation*, that is, by using real-time data at locations within the model regime. Data assimilation is an area of numerical modeling that is presently in a fairly rapid stage of development and there are a variety of techniques being developed and tried (MALANOTTE-RIZZOLI, 1996). In oceanographic models most experience in data assimilation has been with models making predictions at longer time scales (e.g., two weeks [mesoscale] to months and years [climate]), where one basically gets the model back on track and it keeps going without too much problem. However, here we are concerned with phenomena with much shorter (hourly) time scales. The simplest (and least expensive in computer time) data assimilation methods (often referred as *nudging*) involve forcing the model to be 'correct' at locations where there are real-time data and letting the model propagate the difference between the real-time data and the model nowcasts to the rest of the model in some (hopefully appropriate) way. More sophisticated methods involve changing the forcing fields in different ways until the difference between the data and the nowcasts are some least-squares minimum. Such methods involve running the model more than once and could take too long to produce results helpful to the mariner (unless one has a great deal of computing power).

Skillful water level and current forecasts from a port or bay model system ultimately depend on skillful weather forecasts. They also must be initialized by accurate nowcasts which may have used some type of data assimilation. The effect of a good nowcast with which the forecast is initialized can last six hours into the forecast, or perhaps longer in some cases. Thus, water level forecasts from the U.S. East Coast model (used to drive the Chesapeake Bay and Port of NY/NJ models) can be improved by assimilating water level data from the gauges along the U.S. East Coast into the previous nowcasts.

The skill for nowcast and forecast currents is almost always going to be less than the skill for nowcast and forecast water levels, because currents change dramatically over short horizontal distances, especially if the depth changes significantly over that distance, or the channels bend, or several channels meet. To predict the current shears and eddies that can be found in such locations a very high-resolution grid is needed for the model, but this can be very expensive in computer time. An alternative approach is to put a high-resolution nested grid at only those locations where such detail is needed. Model-predicted current fields must be verified by towing an ADCP back and forth over the area for several tidal cycles or more.

VESSEL RESPONSE PREDICTION SYSTEMS

Progress In Understanding Dynamic Draft

Vessel Response Predictors (VRP's) are formulas or computer models used to predict the dynamic draft of a ship in motion. A VRP will usually include the prediction of static, dynamic, and wave-induced responses of vessels under any combination of environmental conditions and operating parameters of the ship.

The *static* component of VRP is basically the ship's reaction to the static displacement of the fluid media (i.e. the water, which will be of some density and may include some amount of suspended sediment). If the total weight of the vessel is less than or equal to the total weight of the displaced fluid, then the vessel floats. The UKC depends on the volume of the fluid that must be displaced to float the vessel, the shape of the hull, and the water depth. UKC of a floating vessel at any geographic point will vary in the same sense as the density at that location, since greater volumes of less dense fluid must be displaced (than of a fluid of greater density) and the ship will sink lower into the fluid. (For example, a full-form ship with a draft of 15 m in open sea may experience an increase of up to 45 cm in draft when entering a port that is significantly fresher than sea water.)

A floating vessel, as a rigid body, can move in six different ways, i.e., translating motions along the x, y. and z axes (surge, sway, and heave), and rotating motions around these three axes (roll, pitch, and yaw). The vessel is also subject to *bending*. These motions can affect the ship's draft and thus its UKC. A floating vessel's *static orientation* from vertical will depend on the spatial distribution of vessel mass. If locally the weight of the vessel (including its load) is not equal to the weight of the locally displaced fluid, a floating vessel may assume an orientation such that a line from the center of buoyancy to the center of weight will not be parallel to the local gravity vector. If the center of total buoyancy compared to the center of weight is displaced to either the port or starboard side of the local gravity, the vessel is said to have a *list* to port or starboard, respectively. If the center of buoyancy compared to the center of weight is either displaced forward or displaced aft of the local gravity, the vessel is said to be *trimmed* by the bow or trimmed by the stern. Tankers and container ships, which have large sections of flat plate keel, will experience an increase in static draft and thus a decrease in UKC in conjunction with a static list. Longitudinal nonuniformities of the local weights of the vessel and its load (compared to the local weight of the displaced fluids) cause the vessel hull as a whole to bend in a longitudinal vertical plane. This bending is termed *hogging* or *sagging*, depending on whether the bending causes tension or compression, respectively, in the bottom of the vessel. Static hogging and sagging may both result in a reduction in the UKC.

When a ship is moving, the dynamic components of VRP are basically settlement and changes in trim (termed together as *squat*), and heeling (due to turning). These responses are termed dynamic because the vessel must be moving to experience these responses. The movements are basically: (1) traversing through the water, a maneuver that tends to persist for long periods of time and (2) turning while traversing through the water, a maneuver that tends to persist for periods that are long compared to the period of surface waves. The dynamic responses of a vessel may change the UKC of a vessel.

There is an existing knowledge base concerning squat, heel, and other hydrodynamic phenomena that cause problems for vessels operating in very restricted waterways. This knowledge base was developed because small clearances between a ship's keel and the seabed are readily equated with the realistic possibility that the ship may hit the sea bottom or that the ship may behave in a manner such that it is difficult to anticipate and/or control the trajectory of the hull (FERREIRO, 1992).

When a vessel is turning steadily, it is acted upon by a force directed away from the center of the circle traversed by the vessel, which moves the center of buoyancy laterally with respect to the center of weight. The vessel response is similar to static list and the vessel is said to be heeling to starboard or to port. The magnitude of the heeling depends on the vessel speed, turning radius, and the transverse metacentric height. Vessels like tankers and container ships that have wide beams and large sections of flat plate keel may experience a dramatic decrease in UKC in conjunction with a heeling.

Theoretical investigations concerning squat stem from the mid-1960's (TUCK, 1966). The early studies indicated that the squat should increase with the square of the ship speed. A typical surface ship, with beam and draft both significantly less than the length, moving through water will force the water particles to move away in both the horizontal and vertical directions. According to BERNOULLI'S theorem, that movement will produce a change in the pressure field around the hull. The reduction in pressure in the vertical produces a depression around the hull, which moves with the hull. Depending on particulars of the hull form, the shape of the depression may vary along the length of the hull and thereby induce a change in the trim of the vessel. The shape of the depression towards the stern of the vessel will vary depending on whether the propeller action is causing the ship to accelerate, maintain constant speed, or decelerate.

The early simplified squat predictors did not depend on ship size, detailed ship geometry, or water depth, and thus tended to overestimate squat. Two notable additions to the squat knowledge base were the inclusions of the effects of side walls (TUCK ,1967) and the effects of finite depths. Since that time, different investigators have introduced multiple non-dimensional parameters, such as length-to-beam ratio and blockage coefficient, into the problem (DAND and FERGUSON, 1973; BARRASS, The extensive knowledge base relative to vessel squat reveals that existing techniques for predicting squat are imprecise (MILLWARD, 1992; VANTORRE, 1996). To improve on the conservative (over-predicting) estimates of squat based on highly stylized methodologies, it is necessary to validate and/or adjust the results of scaled-ship model work or computer studies with actual full-scale measurements of squat. Furthermore, those full-scale measurements must be conducted in particular reaches of any given waterway under a variety of operating conditions, including accelerations, decelerations, static draft and trim, residual flow fields, and still-water depths. OTF-GPS technology is a tool that can be used for full-scale measurements of three-dimensional ship trajectories as they are passing in or out of harbors. Those trajectories, in conjunction with accurate knowledge of the seabed, readily yield UKC time histories of the ships. Such UKC information can be very accurate and may serve as a basis for validation of a VRP system's prediction of a ship's squat and heel under the given environmental conditions and operating parameters of the ship.

The wave-induced components of VRP that impact UKC are heave, roll, and pitch. Given that a ship is traveling in a typical random sea, the ship is subject to heaving, rolling, and pitching. The amplitude of the three modes of periodic motion is influenced mainly by such factors as the ratio of ship-to-wave length, wave height, angle between the ship's course and direction of wave advance, and ship's speed. In general, a vessel will fully respond to the regular rise and fall of the local water surface when the effective spatial wavelength of the waves encountered from any direction is greater than or equal to the projected dimension of the vessel in that direction. As the spatial wavelengths of the directional waves become short compared to the respective projected dimension of a vessel, the vessel responses at those frequencies reduce in amplitude and shift in phase compared to the waves encountered. Statistical approaches are required to describe the vertical motion of the vessel due to its heave, roll, and pitch responses to a directional wave field(WEBSTER and TRUDELL, 1981). Within the duration of a single transit, the time history of the motions of a vessel can be described by a stationary zero-mean narrow-banded Gaussian process. This allows the extreme wave-induced downward vertical motion of any point along the hull of a vessel to be estimated using the method of OCHI (1973) for any particular transit of a waterway (SILVER and DALZELL, 1997).

The several components of VRP are essentially independent and superimposition of the expected static, dynamic, and wave-induced responses of the ship can ensure a certain level of confidence as to the maximum immersion depth of any part of the ship hull relative to the water's surface. A few UKCM systems are presently operating which do include some type of dynamic draft calculation based on vessel response to environmental conditions. These include systems in the Netherlands (PRINCE, 1996), in Australia (O'BRIEN, 1997), and in the United States (SILVER and DALZELL, 1997).

On- the- Fly GPS Measurement of Dynamic Draft

OTF-GPS is widely used to provide vertical reference in a number of applications, such as use in airborne topographic systems with respect to the World Geodetic System 1984 (WGS-84) ellipsoid (REED, 1994) and in the establishment of tidal datums and water surface slopes (DELOACH, 1996). OTF-GPS has been used in the assessment of the effect of squat on hydrographic launches (HUFF, 1995; GODIN and MARREIROS, 1998). The utilization of OTF-GPS for determination of the vertical trajectory of large ships has also been reported by several investigators (HEWLETT, 1995; FENG and KUBIK, 1996).

Given the tendency for hogging and sagging that is typical of container ships, it is not possible using rigid body analysis techniques to accurately describe the vertical movements of one point on a container ship versus the known vertical movements of another separated point along the ship. To adequately describe vertical motions along a container ship it is necessary to instrument the ship at several positions along the full extent of the hull. Figure 5 pictures the outline of a large container ship that has been outfitted with several dual-frequency GPS receivers. The GPS phase observables from those receivers were recorded at one-second intervals onboard the ship and later processed using OTF-GPS techniques in conjunction with one-second GPS phase observables recorded at a local reference station. The measured vertical trajectories of the two GPS antennas, mounted port and starboard on the bridge, each contain the signature affects of vessel heeling and rolling. An average of the two bridge trajectories suppresses the heel and roll but preserves the effects of squat on center keel draft.

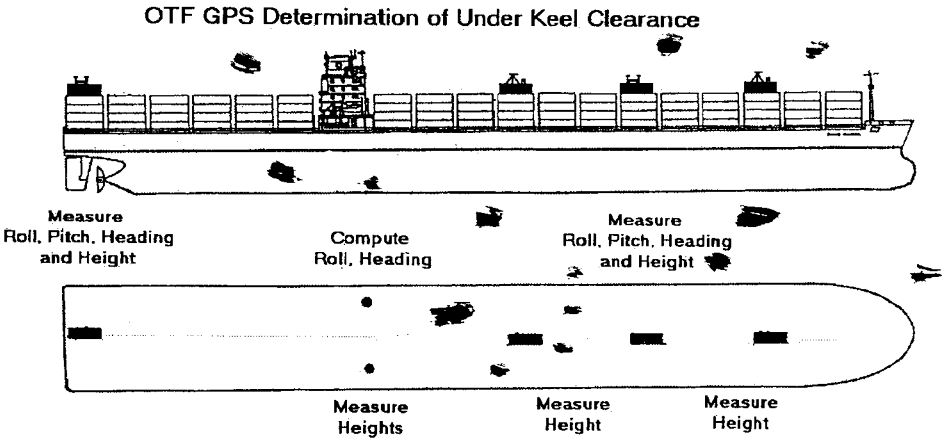


FIG 5.- Schematic layout of multiple GPS antennas/receivers on a container ship for the study of squat

Figure 6 shows vertical trajectories for the bow and aft sections of a typical container ship transiting San Francisco Bay, as determined by OTF-GPS. The figure shows the container ship departing from the Outer Harbor in the Port of Oakland, California, transiting through San Francisco Bay, through the main channel at the San Francisco Bar, and, after the pilot disembarks in the pilot area, an early portion of the coastwise voyage to the next port of call. The variations in the vertical trajectories of bow and bridge (aft) antennas on the container ship result from changes in the static and dynamic components of vessel response due to changes in vessel speed, as well as to changes in the density and depth of the water. Those two-hour time histories of bow and aft vertical trajectories, in conjunction with accurate knowledge of the depths along the approximately 40-km course, readily yields information on the ship's UKC. Such UKC information can be very accurate and may serve as a basis for validation of predicted ship's squat under the given environmental conditions. Figure 7 illustrates how these vertical trajectory data are translated into UKC information. The ellipsoidal heights of an antenna are determined via OTF-GPS and then, using solid body transfer, the ellipsoidal height of the ship bottom is determined. Note that solid body transfer uses rigid body analysis but is constrained for translation between points that are separated only in the vertical. Therefore, the longitudinal rigidity of the hull does not enter into the analysis. It is also important to note that Figure 7 depicts the height of the seabed in ellipsoidal reference. This is contrary to conventional hydrographic surveys that reference the survey depths to a tidal datum, which in the United States is MLLW. However, geospatial variation in the difference between the ellipsoid and MLLW over a survey area can be determined by using a numerical hydrodynamic model to calculate the geospatial variation of MLLW.

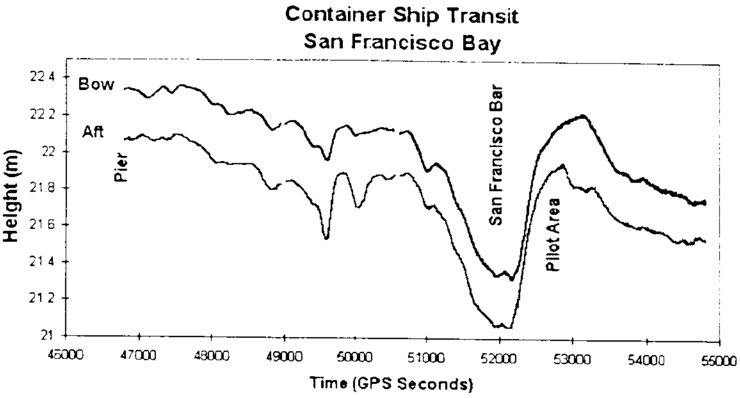


FIG 6.- Vertical trajectories for the bow and aft sections of a container ship leaving a pier in the Port of Oakland and transiting San Francisco Bay, as determined by OTF-GPS. The ship's transit covered approximately 40 km in about 2 hours.

IMPROVEMENTS IN HYDROGRAPHIC SURVEY AND NAUTICAL CHART SYSTEMS

Depth soundings and underwater wrecks/hazards, presented on nautical charts, have always been a basic component of UKC determination. The accuracy of this information depends on the methods used to obtain the hydrographic data, as well as the methods used to reference these data to a tidal datum. The uncertainties in the data translate directly into uncertainties in UKC. The accuracy of the depths and underwater hazards found on nautical charts also depends on how much the sea bottom has changed since the hydrographic data (on which they were based) were acquired. When new data are acquired from a hydrographic survey or a dredging survey, it is important that the data are quickly processed and transformed into cartographic information on a chart. And still another factor in using a chart in the determination of UKC is how easily the information can be used and correctly understood by the mariner. Recent advances in hydrographic and cartographic systems have led to more accurate data that are provided more quickly to the mariner in more useful forms. Further developments in these systems will contribute to further improvements in UKC management.

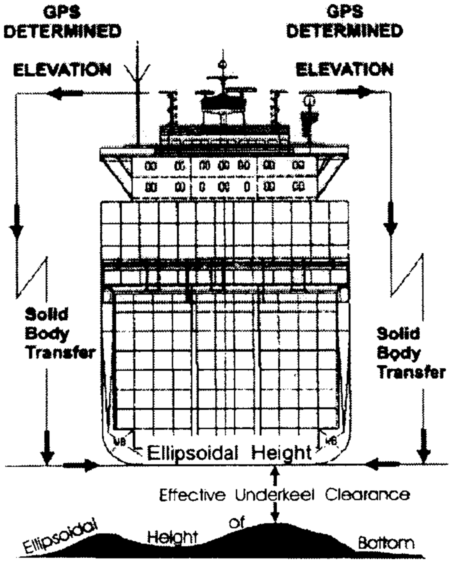


FIG 7.- Diagram illustrating the determination of keel height from measured GPS antenna height and consequently determining UKC by combination of keel height with bottom height.

Acquiring More Accurate Hydrographic Data More Efficiently

There have been great strides in survey technologies leading to increased efficiency and accuracy with which hydrographic data are acquired. This technology has improved the likelihood that all potential dangers to navigation are detected and accurately located in the course of a hydrographic survey.

Multibeam sonar is a technology that was considered new and innovative for shallow-water surveys only a decade ago. Shallow-water multibeam survey systems (SWMSS) became very well represented in the published hydrographic literature, starting in the mid 1980's and continuing to the present, as manufacturers brought new products to the market and the results of testing and operations were reported at national and international symposia. The diversity of SWMSS has grown and continues to grow dramatically. SWMSS are now widely accepted and respected tools for hydrography surveys, allowing full-bottom-coverage surveys of critical navigation areas where UKC issues are important. The initial SWMSS provided swath coverage widths a little less than twice the water depth and there was considerable activity to demonstrate its accuracy and utility to hydrographers. Now many manufacturers and operators of SWMSS claim to have accuracies consistent with IHO S-44 standards over swaths up to eight times water depth.

SWMSS are generally accepted as having the capabilities to provide accurate and detailed documentation of the configuration of the natural seabed and/or maintained channels, as well as the geographic positions of discrete obstructions or shoal areas. To acquire the later more accurately, side-scan sonar technology has often been used. One unique survey tool for the detection and documentation of wrecks and obstructions that NOAA has recently begun operating is a high-speed high-resolution side-scan sonar system (HSHRSSS) (HUFF and WEINTROUB, 1992). Through the high quality of its data and its increased allowable tow speeds, this new technology presents a great improvement in productivity. In fact, the biggest challenge at the moment with both HSHRSSS and SWMSS has been how to efficiently handle the huge quantities of data that these systems produce.

With regard to managing UKC, it is important to be particularly mindful of how accurately the depth data (acquired during a hydrographic survey) are referenced to a chart datum such as MLLW (HUFF and GALLAGHER, 1996; WELLS and VANICEK, 1996). Determining depths with respect to chart datum meant subtracting the water level from the depth measurements. This traditionally required the installation of tide gauges in the area of the hydrographic survey (in addition to the nearest permanent reference gauge already operating) and some technique for interpolating or extrapolating the water level from these few gauges to all other points in the survey area (e.g., a *tidal zoning* technique). Such zoning techniques often involved representing the spatial variation of the water level in terms of connected polygon 'zones' based on the variation in tide range and times of high and low water. The drawbacks of such methods included: (1) treating the variation of the water level as though it were exclusively tidal (when the wind-induced component could vary spatially and temporally in a much different way than the tide); (2) the sudden jumps in value when crossing the boundary between two polygon zones; and (3) the constant time differences assumed between the tide at two geographic points over all astronomical tidal situations over a month.

If wind effects are important in the real-time or forecast water levels used in the UKC determination of ships entering a port, then wind effects are just as important when a hydrographic survey ship is trying to accurately measure depths with respect to chart datum. Water level zoning techniques in an area to be surveyed can be improved by using a numerical hydrodynamic model to provide the geospatial variation of all major tidal constituents, which can then be used to accurately predict the tide at any point in space at any time. These tidal predictions can be added to a geospatial variation in the wind-induced signal (obtained by a model-based interpolation/extrapolation of the residual water level signal at the gauges) to provide the most accurate water levels to be subtracted from the measured depths. Less computer intensive interpolation techniques can also be used to provide such *continuous water level zoning*, such as a Laplacian technique (HESS, 1998).

An even more attractive approach for accurately measuring depths with respect to a common (chart) datum involves the use of differential GPS on a moving ship and techniques for rapid ambiguity resolution, presently referred to as on-the-fly (OTF) GPS. If the transducer of a SWMSS is at a known position below a GPS receiver on the ship, then the depth measurements taken are known relative to the WGS-84 ellipsoid. If the geospatial variation of the tidal datum (e.g. MLLW) with respect to the ellipsoid is determined in advance, then the measured depths can be directly referenced to the chart datum, and no water level zoning processing is necessary. This geospatial variation in the chart datum (with respect to the ellipsoid) can be determined with a numerical hydrodynamic model (SCHMALZ, 1996) or with an interpolation technique such as the Laplacian technique mentioned above. Using OTF-GPS also eliminates the need to correct the depth soundings for all effects on dynamic draft. This GPS approach has been made possible by the centimeter accuracy now achievable in the vertical through the OTF technique. However, using this technology for continuous operation on a moving hydrographic survey ship can lead to occasional data gaps or to the ship having to cease data acquisition at times. The OTF-GPS technique is designed to automatically detect and rapidly repair all carrier phase cycle slips found while processing GPS phase data. The cycle slips during data processing might be caused by multipath (i.e., the corruption of the direct GPS signal by reflected signals from the local surroundings), loss of phase-lock on the signal carrier, or (worst case) by not receiving the signal transmitted from several satellites. The source of the problem resulting in cycle slips might be either the fixed reference receiver, or the moving receiver on the ship, or both. OTF-GPS, with its algorithm for resolution of phase ambiguities, differs from previous kinematic carrier phase techniques where cycle slip problems were addressed by placing the roving receiver's antenna close to the reference station or other known position and having it remain there for many minutes in order for the carrier phase ambiguities to be unquestionably resolved. Furthermore, it was necessary to perform this procedure at the start and end of each survey session. OTF-GPS now solves most carrier phase ambiguities; however, the technique will exhibit reduced reliability with increased distance between the reference and rover. Also, the length of time required to solve carrier phase ambiguities increases with distance between the reference receiver and roving receiver. When conducting a hydrographic survey in an area where overhead structures such as bridges or cranes may cause frequent cycle slip problems, it is necessary to decrease the survey speeds to avoid traveling large distances during the time required for the OTF-GPS algorithm to correctly resolve the carrier phase ambiguities. There are several ongoing research efforts by private industry, academia, and government research units to improve the OTF-GPS algorithms by further increasing the operating distances and by further reducing the number of GPS observing epochs required to achieve the rapid ambiguity resolutions that are the hallmark of OTF-GPS.

Charting Developments That Improve UKCM

As mentioned above, quickly processing hydrographic data and transforming it into cartographic information on a chart is important for giving the mariner the latest and most accurate information on which to base UKC decisions. Recent advances in raster and vector digital chart production techniques are allowing hydrographic agencies to develop *rapid update services* that keep their nautical charts continually updated. Combined with a *print-on-demand* capability this allows the mariner to acquire charts with the latest available information. Such information can now be updated within one to three weeks of receiving new information -- a dramatic difference from the six-month to a year time periods it used to take to put out a revised chart.

This same digital chart capability has, of course, led to the development of electronic nautical charts (ENC's) and electronic chart display and information systems (ECDIS's) (ALEXANDER and GANJON, 1995), which provide not only more user-friendly and accurate ways for a pilot or master to view the bottom of a waterway, but also offer a potential vehicle for UKC prediction over an entire waterway. It has been suggested that real-time (or forecast) water levels could be used to actually change the depths and depth contours displayed on an ECDIS, so that the ship's master or pilot could view expected total water depths at any given time. This is indeed a real possibility, but one must remember that the water level (and its largest component the tide) can vary considerably over distances and thus real-time water levels from one or more gauges cannot be simply added to the all charted depths, nor will simple interpolation between gauges work in most cases. What is required is a nowcast/forecast model system (described earlier in this paper) to provide water levels at hundreds of locations in the bay.or port.

An ECDIS (combined with a water level forecast model system) might even eventually allow for the input of critical ship parameters for determining dynamic draft that could be used to predict UKC along the ship's route based on the planned speed of the ship. Many of the potential benefits of ECDIS result from the basic nature of an electronic chart which facilitates the generation of warnings when certain conditions are satisfied, such as the approach of shoal water (by means of a safety depth and vessel draft). An ECDIS might eventually warn of insufficient UKC somewhere along the ship's remaining route and suggest changes in ship speed to avoid the upcoming problem.

In addition to ENC's and ECDIS, rapid technological developments are enabling dramatic changes in the types of vessel traffic services (VTS) that will be operated to benefit the efficiency and safety of maritime navigation in the world's increasingly congested ports and waterways. In the future it is expected that VTS will involve a digital navigational safety broadcast service and two-way communications that would allow the vessels to inform the VTS center of their operating conditions. While this is usually thought to include information such as vessel identification, position, course, speed and projected travel times to particular restricted areas (ALEXANDER and GANJON, 1995), the two-way communications may someday inform ships that they would be passing sufficiently close to another ship to where the squat-causing surface depressions traveling along with each ship might combine to significantly decrease the UKC of both of the ships as they pass.

CONCLUSIONS

Effective under-keel clearance management (UKCM) is becoming a reality as ports begin to implement real-time and nowcast/forecast model systems, and ships use improved vessel response prediction systems (validated with ship motion data from OTF-GPS studies). These systems will give the ship's master the information he needs to effectively manage his ship's UKC. With accurate charted depths and underwater hazards, water levels, and ship-specific channel-specific prediction formulas for dynamic draft, he can schedule the planned route to ensure that there will be sufficient water level for safe passage when the ship reaches locations with controlling depths, and/or he can take precise actions that affect the ship's dynamic draft (such as changing the speed of his ship) if necessary. For some ports he will also have other information needed for dynamic draft calculations, such as currents, water density, and waves, swell, and/or seiching (which are also important for safe ship maneuvering).

How soon effective UKCM can become operational in a particular port depends on how accurately water level can be predicted, up to 24 hours into the future, which in turn depends on the complexity of the hydrodynamics in and near that port. For many ports the predictive skill of forecast models systems ultimately goes back to the skill of the weather forecast model(s) that drive the coastal ocean and bay models and to the data assimilation and ensemble averaging techniques developed to overcome data deficiencies. Effective UKCM also depends on improving vessel response prediction systems by measuring the ship motions of bulk carriers, container ships and oil tankers, and their dynamic draft, for varying environmental conditions, using OTF-GPS techniques. Shallow-water multibeam sonars and high-speed high-resolution side-scan sonars have already improved the accuracy and efficiency of obtaining new hydrographic data on depths and underwater hazards. The challenge to efficiently process the huge quantities of data produced by these systems is in the process of being met. Improvements in continuous water level zoning techniques will also improve the accuracy of the new depth data; and further improvements in both survey accuracy and efficiency will result as OTF-GPS is used regularly in hydrographic surveys to provide the vertical reference for the data (tied to a tidal chart datum by using a numerical hydrodynamic model or similar technique). OTF-GPS techniques will continue to improve in reliability as techniques for rapid ambiguity resolution improve. The rapid update services being developed to keep electronic charts current will ensure that the mariner has access to the latest depth and hazard data. An ECDIS using these data will be able to dynamically change depth soundings and contours using the output from nowcast/forecast model systems, and will also interface with (or incorporate) a vessel response prediction system.

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