CHAPTER 25

DOPPLER SONAR NAVIGATION

INTRODUCTION

2500. Doppler SONAR Velocity Logs

Significant improvements in maritime navigation can be obtained by the use of **Doppler Velocity Logs (DVLs)**. These acoustic sensors take advantage of the Doppler principle to provide a very accurate measure of the 3-dimensional velocity of a platform relative to the ground or to the ocean. The velocity over ground measured by the DVLs is much more accurate than can typically be achieved with a ship's **Inertial Navigation System (INS)**, which makes DVLs essential for missions requiring very accurate velocity and position.

Despite the ubiquity of Global Positioning Satellite (GPS) navigation today (see Chapter 22), the DVL still plays an important role in the suite of navigation instruments for surface vessels and a primary role for submerged vessels. The DVL provides an independent source of ship speed that is more reliable and has less random error than either the direct GPS velocity or the time derivative of GPS position. Also, the DVL is able to provide a navigation solution in situations where GPS cannot be used, for example when passing under bridges or near other structures, or in situations where the GPS signal is compromised due to electromagnetic jamming, spoofing, multipath, or unintentional interference from solar activity, geomagnetic storms, or other sources and for submerged vessels where GPS is not readily available. DVLs may also be used directly to aid an INS (see Chapter 20) by damping Schuler oscillations, aiding gyrocompassing, calibrating gyro and accelerometer bias and alignment errors, and controlling the medium-term growth of position error and the long-term growth of velocity error. Some DVLs can also provide measurements of current velocity near the vessel that may be useful in navigation and ship handling.

When anchoring large surface vessels without the aid of tugs, the speed over ground should be less than 0.3 knot to avoid accidental loss of the anchor and chain. The DVL is better than GPS at providing precise velocity information for this kind of operation. The DVL also can serve as a backup to laser- and radar-based docking aids for large surface vessels to maintain safe docking speeds in the event of failure of those systems.

The integration of GPS receivers into airborne and surface vehicles provides these vehicles with an increase in navigational accuracy that is unavailable to underwater vehicles. The navigation systems for underwater vehicles must rely on an inertial navigation system, a velocity log and gyrocompass, an array of transponders, or a combination of these systems. Although these navigation systems may be initialized with a GPS position fix, once the vehicle is submerged, the navigation system must operate autonomously. Recent improvements in the performance of bottom-tracking DVLs provide underwater vehicles with autonomous navigation accuracies on the order of 0.2 percent of distance traveled. However, vehicles equipped with a DVL are limited to operating at lower altitudes above the ocean bottom.

THE DOPPLER PRINCIPLE

2501. The Doppler Principle

This section introduces the Doppler principle and how it is used to measure relative radial velocity between different objects. The **Doppler effect** is a change in the observed sound pitch that results from relative motion. An example of the Doppler effect is the sound made by a train as it passes (Figure 2501). The train's whistle has a higher pitch as the train approaches an unmoving observer, and a lower pitch as it moves away. This change in pitch is directly proportional to how fast the train is moving. Therefore, by measuring the change in the pitch the speed of the train can be calculated.

Sound consists of pressure waves in air, water or solids. Sound waves are similar to shallow water ocean waves.

- **Waves**. Water wave crests and troughs are high and low water elevations. Sound wave crests and troughs are high and low air pressure.
- **Wavelength** (λ). The distance between successive wave crests.
- **Frequency** (f). The number of waves that pass in a unit of time.
- **Speed of Sound** (C). The speed at which the waves propagate.

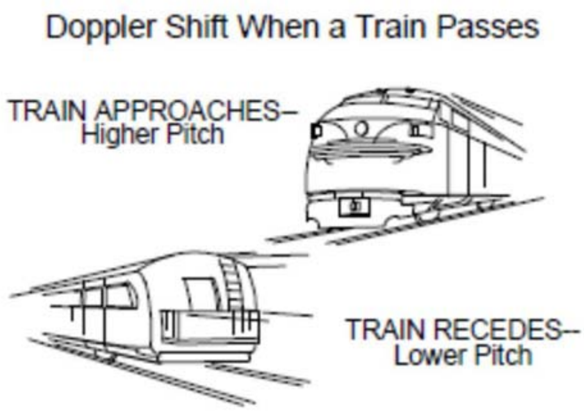

Figure 2501. When you listen to a train as it passes, you hear a change in pitch due to the Doppler shift. Courtesy of Johns Hopkins University - Applied Physics Laboratory.

Speed of Sound = Frequency x Wavelength

$$C = f\lambda$$

Example: A wave with a 300 kHz frequency and wavelength 5 mm will travel at (300,000 Hz) X (.005m) = 1500 meters per second.

Suppose while standing still near water, an observer sees eight waves pass in a given time interval. If the observer starts walking forward toward the waves more than eight waves will pass by in the same time interval, thus the wave frequency will appear to be higher. Similarly, if the observer walks in the opposite direction, away from the waves, fewer than eight waves pass by and the frequency appears lower. This is the Doppler effect. The **Doppler shift** is the difference between the frequency observed when standing still and that observed when moving.

Example. Standing still and you hear a frequency of 10 kHz, and then you start moving toward the sound source and hear a frequency of 10.1 kHz, then the Doppler shift is 0.1 kHz.

The equation for the Doppler shift in this situation is:

$$Fd = Fs(V/C)$$

Where:

- *Fd* is the Doppler shift frequency.
- *Fs* is the frequency of the sound when everything is still.
- *V* is the relative velocity between the sound source and the sound receiver (the speed at which you are walking toward the sound; m/s).
- C is the speed of sound (m/s).

Note that:

- If you walk faster, the Doppler shift increases.
- If you walk away from the sound, the Doppler shift is negative.
- If the frequency of the sound increases, the Doppler shift increases.

DVLs use the Doppler effect by *transmitting* sound at a fixed frequency and *listening* to echoes returning from either sound scatterers in the water or reflected off the ocean bottom. Sound scatters in all directions from scatterers or off the reflected surface. Much of the sound goes forward and is not reflected back. The small amount that reflects back is Doppler shift.

In the case of a DVL mounted on the underside of a vehicle, the vehicle is both a moving transmitter and receiver. The intermediate reflection of the acoustic signal off a water borne scatter or at the ocean bottom is treated as a stationary receiver immediately followed by a stationary transmitter. Because the DVL both transmits and receives sound, the Doppler shift is doubled.

$$Fd = 2Fs(V/C)$$

2502. DVL Transducers

The acoustic transmission and receiver in a DVL is accomplished with transducers. Acoustic transducers are transmitters that convert electricity to sound and also receivers that convert sound to electricity. The active elements in transducers are piezoelectric ceramic disks that expand or contract under the influence of an electric field. The electric field is applied through thin layers of silver deposited on the surfaces of the ceramic. When a voltage is applied, the disk gets thicker or thinner, depending on the polarity of the voltage. The ceramic disk is potted (encased) with polyurethane in a metal cup with a reflective backing material. Transducer quality is essential for data quality.

Figure 2502a. For more information on Janus. http://en.wikipedia.org/wiki/Janus

DVL transducers are normally deployed using the Janus configuration, named for the Roman god Janus often depicted as having two faces looking in opposite directions (see Figure 2502a), which employs four ultrasonic beams, displaced 90° from each other in azimuth, with each directed obliquely at the ocean floor at angle θ_J from the vertical, to obtain true ground speed in the alongship and athwartship directions. The angle θ_J, typically 30°, is known as the Janus angle. Because the DVL combines information from all beams to determine velocity, there is no required orientation for the DVL relative to the ship. The two most common orientations are with opposing beams aligned to the alongship axis (Figure 2502b) or rotated 45° to have two beams pointing forward and two beams aft. Velocity components are measured in the direction of each beam using the Doppler effect on the backscattered acoustic signal. A development of the equation for these beam component measurements from the fundamental Doppler equation for sound propagation is presented in Section 2506.

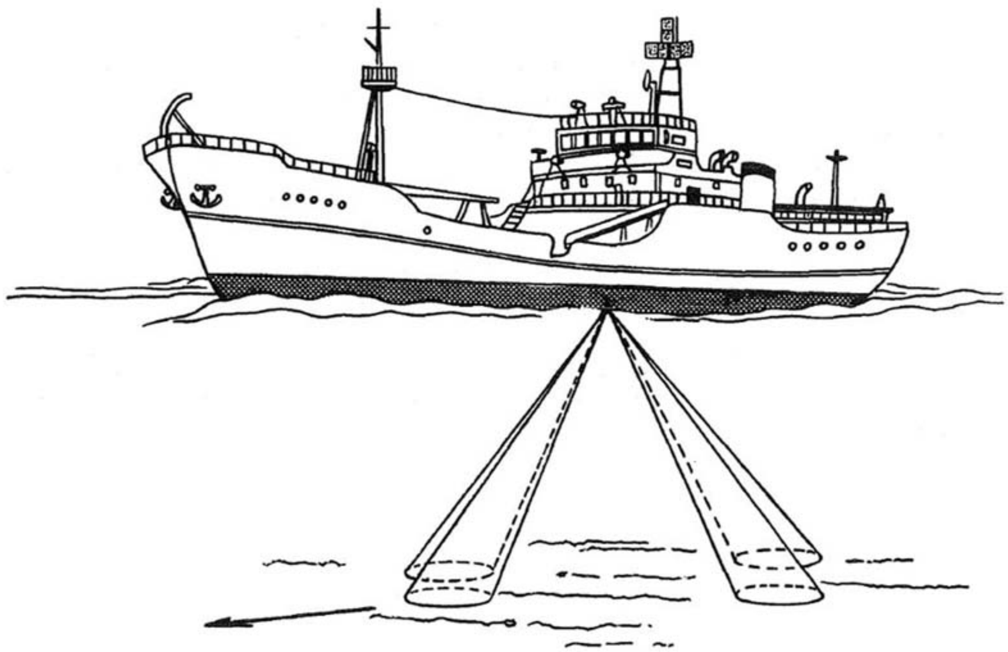

Figure 2502b. Janus configuration.

The advantage of the Janus configuration when the beams of one or both opposite pairs are pinged simultaneously is that the velocity differences within beam pairs that measure the horizontal velocity component are not affected by pitch or heave differences between beams that might occur were pinging to occur separately, nor by the large tilt- and heave-induced errors that could result if only one beam were used in each of the alongship and athwartship directions.

The Doppler theory equations for computing velocity for each DVL beam are given in Section 2506. Typical DVLs employ four-beams to measure three dimensional velocity of a vessel. A system such as this is over-determined as there are more beams than necessary. There are a number of potential solutions for going from a four beam velocity to a three dimensional velocity. The classic solution for solving over-determined systems is to use least squares (Brokloff, 1994).

An alternate approach is to use the redundant 4th beam to compute a direct measurement of a quality control output known as "error velocity" described in detail below. When the magnitude of the error velocity is unusually large for a particular ping and a bad measurement on a single beam can be identified as the cause, the remaining three beams can still be used to accurately determine the velocity vector.

The vector V_b of four beam-wise velocity components can be converted to the augmented velocity vector V_{inst} in the DVL instrument frame of reference by multiplying on the left by the beam-to-instrument transformation matrix *B*:

$$V_{inst} = B \cdot V_b$$

$$\text{where } V_{inst} = \begin{bmatrix} u_{inst} \\ v_{inst} \\ w_{inst} \\ e \end{bmatrix}, \qquad V_b = \begin{bmatrix} V_{pd} \\ V_{sb} \\ V_{fb} \\ V_{ab} \end{bmatrix},$$

and normally,

$$B = \begin{bmatrix} \frac{-1}{2\sin\theta_J} & \frac{1}{2\sin\theta_J} & 0 & 0 \\ 0 & 0 & \frac{1}{2\sin\theta_J} & \frac{-1}{2\sin\theta_J} \\ \frac{-1}{4\cos\theta_J} & \frac{-1}{4\cos\theta_J} & \frac{-1}{4\cos\theta_J} & \frac{-1}{4\cos\theta_J} \\ \frac{-1}{2\sqrt{2}\sin\theta_J} & \frac{-1}{2\sqrt{2}\sin\theta_J} & \frac{1}{2\sqrt{2}\sin\theta_J} & \frac{1}{2\sqrt{2}\sin\theta_J} \end{bmatrix}$$

and where u_{inst}, v_{inst}, w_{inst}, and e are respectively the nominally starboard, forward, upward, and error velocity components in the instrument frame and V_{pb}, V_{sb}, V_{fb} and V_{ab} are respectively the measured velocity components in the outward direction of the port, starboard, forward, and aft beams. (The beam labels correspond to their nominal azimuth directions in the first common orientation described above.)

Note. Many manufacturers use an inward-positive convention for beam velocities instead, which negates the signs of all elements of the beam-to-instrument matrix *B*. The outward-positive convention is used here to aid intuition when discussing the Doppler effect on the forward beam.

In general, the first three rows of *B* are the Moore-Penrose pseudoinverse of the 4×3 beam direction matrix having four rows, each row being the unit vector in the outward direction of a beam. These unit vectors can be determined during factory calibration. The elements of the B matrix shown above are the nominal values to be expected if there are no manufacturing deviations in beam orientation.

The last row of *B* is constructed to be orthogonal to the other three rows and normalized to make its magnitude (root-mean-square) match the mean of the magnitudes of the first two rows. It corresponds to the error velocity *e*, extra information in V_{inst} that augments the velocity vector comprising the first three of its elements. Its scaling was chosen so that the variance of the error velocity should have the same expected value as the portion of the variance of either of the two horizontal velocity components attributable to instrument noise rather than vessel motion. The expected value of the error velocity is zero.

The error velocity is useful for screening to exclude improbable measurements. In cases where the magnitude of the error velocity is unusually large compared to its standard deviation and the bad beam can be identified by, for example, the fact that its correlation coefficient is much lower than that of the other three beams, then the redundancy provided by having four beams allows the velocity vector to be determined by using the valid measurements from the three remaining beams. The algorithm that does this is equivalent to setting the error velocity e to zero and solving the equation corresponding to the last row of matrix *B* for a value to replace the rejected measurement from the bad beam, then continuing with processing as if all four beam measurements were known.

If the vessel's pitch and roll measurements are available from a gyrocompass, vertical gyro, or other sensor, they can be used to implement a coordinate frame rotation to give leveled horizontal velocity components in any sea state. This is known as the leveled ship frame. Likewise, heading from a magnetic compass, two-antenna GPS compass, gyrocompass, or INS can be used to calculate the velocity components in the geographic frame. These steps are shown in detail below.

If the DVL is not installed precisely aligned with the vessel axes, it is convenient to first rotate the measured velocity vector from the instrument to the ship frame using a constant alignment rotation matrix *A*:

$$V_{ship} = A \cdot V_{inst}$$

where $V_{ship} = \begin{bmatrix} u_{ship} \\ v_{ship} \\ w_{ship} \end{bmatrix}$, and

and nominally,

$$A = \begin{bmatrix} CH_A CR_A + SH_A SP_A SR_A & CH_A SP_A SR_A - SH_A CR_A & -CP_A SR_A & 0 \\ SH_A CP_A & CH_A CP_A & SP_A & 0 \\ CH_A SR_A - SH_A SP_A CR_A & -(CH_A SP_A CR_A + SH_A SR_A) & CP_A CR_A & 0 \end{bmatrix}$$

and the abbreviations *C* for **cos** and *S* for **sin** have been made in matrix ***A*** for notational convenience. The three angles H_A, P_A, and R_A respectively represent the heading, pitch, and roll *of the vessel* necessary to make the instrument be level and heading so the nominally-forward beam points north. For example, if the "forward" beam is installed to point 45° to port but is otherwise level, you would nominally use $H_A = 45°$, $P_A = 0°$, and $R_A = 0°$. Calibration of H_A, P_A, and R_A is discussed in the next section. When these angles are small, they essentially act as angle offsets that respectively subtract from the effective heading, pitch, and roll applied in the next velocity rotation steps discussed below. Of course, there are many possible ways to define the alignment matrix ***A***; this one has the advantage of keeping the adjustment angles well-defined and unambiguously communicated as ship attitudes. If the vessel's heading and attitude sensors are used with the DVL, then the rotation by ***A*** is necessary to align the velocity measurement with the axes of those sensors. Otherwise, this step is merely a convenience to allow the DVL's internal sensors to measure and report the vessel's heading and attitude instead of its own. In either case, the heading, pitch, and roll can be considered to be those of the vessel, not the instrument.

The next step is to rotate the velocity from the ship frame to the leveled ship frame by removing the effects of pitch P and roll R:

$$V_{level} = L \cdot V_{ship}$$

where $$V_{level} = \begin{bmatrix} u_{level} \\ v_{level} \\ w \end{bmatrix}, \text{ and}$$

$$L = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos P & -\sin P \\ 0 & \sin P & \cos P \end{bmatrix} \cdot \begin{bmatrix} \cos R & 0 & \sin R \\ 0 & 1 & 0 \\ -\sin R & 0 & \cos R \end{bmatrix} = \begin{bmatrix} \cos R & 0 & \sin R \\ \sin P \sin R & \cos P & -\sin P \cos R \\ -\cos P \sin R & \sin P & \cos P \cos R \end{bmatrix}$$

According to the right-hand rule convention used here for the leveled ship frame, u_{level} is the drift to starboard, v_{level} is the forward speed of the vessel, and w is the upward velocity component.

If the velocity is desired in the geographic frame instead of the leveled ship frame, say for dead reckoning purposes, the velocity can be rotated yet again using the heading H:

$$V_{geo} = G \cdot V_{level}$$

where $$V_{geo} = \begin{bmatrix} u_E \\ v_N \\ w \end{bmatrix}, \text{ and}$$

$$G = \begin{bmatrix} \cos H & \sin H & 0 \\ -\sin H & \cos H & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and u_E and v_N are respectively the east and north components of the horizontal velocity.

2503. DVL Operational Errors

Long-term, systematic errors can be divided into instrument errors inherent to the technology, discussed in the next section, and operational errors that may be ameliorated by the user through proper installation, calibration, operation, and choice of accessory sensors, which we address here. Operational errors may be classified as *alignment errors, vessel motion induced errors, velocity of sound errors, interference errors, measurement outliers*, and *power loss errors*.

Alignment errors. If the DVL is not properly aligned with the compass's lubber's line, a dead-reckoned course will show a cross-track drift from the true course when compared to GPS. When using a magnetic compass, it may be difficult to distinguish this misalignment from compass variation. Most DVLs accept a calibration correction similar to H_A in the previous section to offset one or both of these angular errors.

When no pitch and roll measurements are available and the DVL is not level, or when the DVL is not properly aligned with the vertical fiducial of the pitch-roll sensor, the velocity measurement will be reduced by a factor equal to the cosine of the mean pitch angle (trim) or its residual error, assuming that the vessel is moving forward without leeway. This error can be detected by the DVL measuring a significant average vertical velocity, and the pitch error can be measured as the arctangent of the ratio of average vertical velocity (w) to average forward velocity v_{level}. This error is generally small; for example, an uncorrected trim (or list) of 4° will reduce the alongship (or athwartship) speed signal by about 0.25%. Calibration of the pitch alignment parameter P_A in the previous section can be accomplished by increasing the value of P_A by $\arctan(\langle w \rangle / \langle v_{level} \rangle)$. Similarly, R_A should be increased by $\arctan(\langle w \rangle / \langle u_{level} \rangle)$, but creating a significant average drift velocity $\langle u_{level} \rangle$ for the vessel may require use of a cross-current, side thrusters, or tugs in order to calibrate

Vessel motion induced errors. While alignment errors are caused by mean attitude offsets, there are additional analogous errors caused by dynamic fluctuations in pitch and roll when these are not measured and corrected. The alongship and athwartship velocity components averaged in the ship frame are biased low compared to averaging in the more stable leveled frame by a factor equal to the cosine of the standard deviation of the pitch and roll fluctuations, respectively. Even in the leveled ship frame or geographic frame, if an inadequate pitch/roll sensor is used that is not gyro-stabilized against contamination by wave-induced accelerations, there will be a similar bias effect multiplying the average horizontal velocity components by the cosine of the standard deviation of the resulting pitch and roll errors.

Analogous errors come from heading fluctuations. Dead reckoning calculation of progress along a course leg should be made in the more stable geographic frame to avoid the bias factor equal to the cosine of the standard deviation of the actual heading fluctuations. Even in the geographic frame, there is a cosine of the heading sensor errors factor that will bias the distance made good low.

Wave-induced motions of the vessel may cause speed fluctuations that may obscure the vessel's average speed over ground, but these fluctuations are not actual errors in the sense that they do reflect the ship's true motion. Some speed logs filter the output by providing a running average over several pings to reduce these fluctuations along with *random instrument errors*, with the unfortunate drawback of introducing a time lag to the speed measurement.

Velocity of sound errors. DVLs having transducers of the piston type directly measure the Mach number for the velocity component along each beam, which must be multiplied by the speed of sound to calculate the beam velocity.

Therefore, the relative uncertainty in the sound speed results in a relative systematic error, or “scale factor bias,” of the same percentage. Although the sound speed varies over the water column and the deflection of sound rays by refraction depends primarily upon the mean sound speed over the water column, the sound speed needed by piston DVLs is that of the water at the transducer location. This is because of Snell's law of refraction, which implies that in horizontally-stratified water, the ratio of the sound speed to the sine of the sound ray inclination to the vertical is preserved throughout the water column. Hence, we must know the sound speed at the point where we know that the ray inclination is the Janus angle, which is at the transducer.

The speed of sound in bubble-free seawater depends upon temperature, salinity, and depth (of importance to submarines), but not frequency. The temperature dependence is the strongest but also the easiest to measure and compensate for in the DVL firmware using an empirical sound speed formula. Salinity is more inconvenient to measure but also less important, the sensitivity of sound speed being only about 0.1% per g/kg of salinity. However, in the brackish water of inlets and estuaries, the uncertainty in the salinity can be significant. In some installations an acoustic velocimeter may be used to directly measure the sound velocity in the vicinity of the transducer. Most commercially available DVLs accept a variety of different forms of sensor input to determine the sound speed factor used to convert Mach number to velocity.

A piston DVL can be mounted behind a flat window made of acoustically-transparent plastic with fresh water between the transducer and the window. The DVL is configured for a salinity of 0 g/kg and refraction at the window face automatically adjusts the Janus angle of the beams outside the window to compensate for the sound speed change due to the salinity of the sea water. Another scheme to avoid sound speed uncertainty is to use plastic prisms between the tilted transducers and the horizontal window, and employ a sound speed formula for the plastic as a function of temperature.

DVLs having phased array transducers not only have the advantage of smaller size by generating all four beams from a single aperture, but also of sound speed independence in the measurement of velocity components in the plane of the array. In fact, for horizontal motion of a level phased array in the direction of a beam azimuth, the Doppler shift is also independent of frequency, being (in hertz) half the ratio of the speed to the array stave spacing. The actual Janus angle doesn't matter to the measurement, although its sine does change slightly in proportion to sound speed and varies inversely with frequency over the bandwidth of the projected signal, always giving the same Doppler frequency shift for a given horizontal speed. In contrast, measurement of the velocity component perpendicular to the face of the phased array does depend upon sound speed, but since pitch is typically small, the propagation of speed-of-sound error into vessel speed is usually negligible.

Interference errors. Acoustic interference from other sonars having fundamental or harmonic frequencies near those used by the DVL can result in altitude error from false bottom lock, velocity bias, and other symptoms of jamming. This problem can be avoided by synchronizing multiple sonars to a ping schedule that avoids simultaneous pinging.

Outliers. While most DVL velocity errors have a nearly Gaussian distribution, unusual random events such as Rayleigh fades and ambiguity errors can occur that cause large errors with a higher probability than a bell-shaped curve would predict. For good performance, especially when dead reckoning, it is important to screen the measurements to remove outliers. DVLs may screen the velocity measurements automatically based upon loss of bottom lock, signal-to-noise ratio (SNR), relative intensity among beams, correlation coefficient, and/or error velocity, usually replacing bad measurements with the value from the previous good ping. Although threshold values for some of these screening tests may be under user control, the factory default settings are adequate under most conditions.

Power loss errors. The DVL requires a certain minimum SNR to detect the bottom and to distinguish the ping echo signal from thermal and ambient acoustic noise. The SNR, and thus the maximum altitude (maximum water depth for surface vessels), is affected by acoustic losses, some of which vary with environmental conditions. The most important of these are the temperature and salinity dependence of acoustic absorption by the seawater and variability in the bottom backscatter coefficient. Usually, increasing temperature decreases the maximum altitude for seawater, although at lower frequencies the best range performance is reached at moderate temperatures. At 30° C the maximum range may be reduced by as much as 30%. The maximum range is significantly greater in fresh water than in seawater.

At water depths near the maximum operational altitude of the DVL, near-surface bubble clouds may reduce the signal strength enough to cause dropped measurements, resulting in non-uniform sampling. If the motion of the vessel through the waves causes the timing of the presence of these bubbles and the resulting dropouts to be correlated with the wave-induced motion, the average of the remaining measurements may be biased. Three additional phenomena that can reduce signal strength in rough seas are (1) greater acoustic attenuation from the greater path length, (2) reduced bottom backscattering strength, both effects largest for a beam at its greatest angle from the vertical at maximum roll, and (3) rotation of the beam away from the direction toward which the sound was projected during the time interval between projection and receipt of the acoustic signal, which is worst at high altitudes and roll rates. Although the timing of these phenomena may vary relative to that of the bubbles, the dropouts they cause may also be correlated with the wave-induced motion of the vessel and thus sources of sampling bias. Therefore, the accuracy of the DVL output may be degraded when there are frequent dropouts in rough seas.

2504. Systematic Instrument Errors in DVLs

DVLs are subject to a number of long-term (i.e., systematic) errors besides those discussed in the previous section, the three most important kinds being *terrain, absorption*, and *sidelobe beam-coupling biases*.

Terrain bias. Because the bottom backscatter strength is a strong function of incidence angle, the side of the beam closer to the vertical is weighted more than the outer side, reducing the effective Janus angle and biasing the velocity low by some percentage. Although a typical value of this bias can be calibrated out, variability in the slope of the bottom backscatter strength function with incidence angle make the terrain bias depend upon bottom type. Flat, muddy bottoms generally give more terrain bias than rough rocky bottoms.

Absorption bias is similar to terrain bias in that it weights the inside of the beam more than the outside, but the cause is acoustic absorption over a shorter or longer path rather than differential bottom backscatter strength. Unlike terrain bias, which is independent of altitude, absorption bias is proportional to altitude and therefore worst at maximum depth. Absorption bias could be corrected if the water properties needed to estimate the acoustic absorption coefficient were known over the entire water column, but since they generally are not, most DVLs do not attempt to make a correction proportional to altitude.

Sidelobe beam-coupling bias is caused by acoustic leakage of the signal from opposite and neighboring beams through sidelobes of the beam pattern of the desired beam. This may become a problem when bottom slope, roll, or some other phenomenon increases the relative intensity of one or more of the unwanted beam contributions or reduces that of the beam being measured. For narrowband DVLs and for broadband DVLs at low speeds, this error behaves as a negative scale factor bias (i.e. the error is proportional to speed). For broadband DVLs at higher speeds, the velocity error is a periodic function of velocity, making its relative size less with increasing speed. Sidelobe beam-coupling bias can be avoided by pinging each beam separately in shallow water or by using different transmitted signals in different beams. Of the three kinds of systematic errors discussed only sidelobe beam coupling bias affects water-relative velocity measurements in the volumetric scattering mode.

All three kinds of systematic errors discussed above are reduced by using narrower beams, which requires either larger transducer diameter or higher frequency. DVLs can be calibrated against GPS to calculate a correction factor to remove these systematic errors, but in general, the correction will not universally apply. For submarines, DVL-aided INSs can calibrate scale factor bias against the more accurate INS accelerometer scale factor by doing turning or speed-changing maneuvers that create accelerations observable by a Kalman filter.

2505. Basic Design Considerations

Beamwidth. Beamwidth should be small enough to keep the systematic errors discussed in the previous section to reasonable levels, yet not so small that vessel motion causes signal loss in heavy seas. The width of the acoustic beam is inversely proportional to the diameter of the acoustic transducer. Most DVLs have transducer diameters between 15 and 30 wavelengths, the number generally lower at lower frequencies because of the greater cost of transducer size for larger systems and the longer acoustic travel time in deeper water causing greater SNR loss due to vessel motion.

Frequency. A high acoustic frequency is desirable for reducing transducer size and maximizing the Doppler phase shift. However, at higher frequencies the absorption loss is very nearly proportional to the square of the frequency. As the frequency is decreased, the loss tends to become linear. As the frequency is reduced to obtain greater maximum depth of operation in the bottom return mode, the transducer size grows increasingly large. Improvement in operating depth diminishes near 100 kHz while transducer size has increased considerably. Therefore, the frequency selected is a trade-off among desired maximum operating depth, transducer size, and cost. The region between 150 and 600 kHz is finding the greatest application.

Transmitted acoustic signal. The bandwidth of the transmitted signal is a programmable design variable. Narrowband transmissions achieve the greatest range at a particular frequency by minimizing thermal and ambient noise, at the expense of more erratic behavior due to stochastic signal fades that can occasionally prevent bottom lock. The narrowband mode also has additional sources of systematic error. In shallow to moderate water depths, where signal-to-noise ratio is not an issue, wider bandwidth produces more stable measurements with less random error. The signal bandwidth can be controlled independently of the duration of the projected pulse by phase-coding the signal. Most DVLs use a pulse duration that is a significant fraction of the travel time in order to fully ensonify the bottom, which greatly reduces the self-noise, one source of random error. In shallow water, the so-called "pulse-to-pulse coherent mode" having particularly low short-term error is also available, in which bottom echoes are received from each of two or more pulses before the next pulse in the transmission has been projected.

2506. Doppler Theory

A DVL relies on incoherent scattering of sound off the bottom, as opposed to specular reflection, so it tracks individual bottom scatterers that are *ensonified* by its beams. As a vessel moves over a sloping bottom, the velocity component measured by a beam will in general be unrelated to the time derivative of the range to the bottom along that beam, the latter being affected by new scatterers entering the beam at a slightly different range that have no velocity themselves.

The frequency of a plane wave signal of a particular wavelength is proportional to the rate of propagation of its phase fronts (pressure crests), which is the sound speed c in a reference frame moving with the water, but the rate is offset from c by the component of vessel velocity perpendicular to the phase fronts (i.e., parallel to the acoustic beam) in a reference frame moving with the vessel. For example, if the vessel is moving with vector velocity $\boldsymbol{V}$ and there is no current, then the forward beam-wise velocity component is $V_{fb} = \boldsymbol{V} \cdot \hat{\imath}_{fb} = u\sin\theta_j - w\cos\theta_J$ where $\hat{\imath}_{fb}$ is the unit outward vector in the direction of the forward-pointing beam. The frequency of the signal projected into the forward beam will be increased by the factor $f_w/f_p = c/(c - V_{fb}) = (1 - M_a)^{-1}$, where f_w is the frequency observed in the water frame, f_p is the frequency projected by the vessel, and M_a is the beam Mach number V_{fb}/c. When there is no current, *backscatter* does not change the frequency of the signal in the water frame, it simply reverses its direction. Upon returning to the vessel, the frequency will increase again by the factor $(1 + M_a)$, for a total of $\frac{1 + M_a}{1 - M_a}$. Subtracting 1 gives the Doppler shift factor:

$$\frac{\Delta f}{f_p} = \frac{2M_a}{1 - M_a} = \frac{2V_{fb}}{c - V_{fb}} = 2\frac{u\sin\theta_J - w\cos\theta_J}{c - u\sin\theta_J + w\cos\theta_J}$$

If this derivation is repeated with one or more water layers moving with the current, it will be found that the current only adds terms of order M_a^2 relative to the measurement, which are negligibly small.

For DVLs with piston transducers, the sound speed c at the transducer must be known to calculate the velocity from the Mach number. For phased arrays, the ratio $2(f_w/c)\sin\theta_J$ is equal to $1/(2d)$, where d is the stave spacing of the array and $f_w = f_p/(1 - M_a)$ is the frequency in the water frame, which is the average of the projected and received frequencies. The Doppler shift is therefore:

$$\Delta_f = 2f_w M_a = \frac{1}{2d}(u - w\cot\theta_j)$$

which is independent of frequency or sound speed for phased arrays in horizontal motion. Hence when $w = 0$, all frequency components of the signal experience the same Doppler *frequency shift* in phased arrays, whereas they experience the same relative *Doppler shift factor* in piston transducers.

The Doppler effect on a signal can alternatively be understood in the time domain as a small change in the time of arrival of repeated portions of the signal, no matter how narrow or wide its bandwidth. In a frame of reference fixed to the water, the point midway between the projection location and the point where the backscattered signal is received is known as the *phase center*. The displacement of the phase center over the lag t_L at which the projected signal repeats is $V\left(t_L - \frac{1}{2}\Delta t\right)$, where Δt is the amount of $V \cdot \hat{\imath}_{fb}\left(t_L - \frac{1}{2}\Delta t\right)$ to the sound displacement $c\,t_L$ in the same interval:

$$\frac{\Delta t}{t_L} = 2M_a\left(1 - \frac{1}{2}\frac{\Delta t}{t_L}\right) = \frac{2M_a}{1 + M_a} = \frac{2V_{fb}}{c + V_{fb}}$$

where the last two expressions come from solving the first equation for $\Lambda t/t_L$, and are equal to $\frac{\Delta f}{f_r}$, where $f_r = f_w(1 + M_a)$ is the received frequency. Solving the equation above for the forward beam velocity V_{fb}, we have:

$$V_{fb} = u\sin\theta_J - w\cos\theta_J = \left(\frac{c}{2t_L}\right)\frac{\Delta t}{1 - \frac{1}{2}\Delta t/t_L} = \left(\frac{c}{4f_0 t_L}\right)\frac{2f_0\Delta t}{1 - \frac{1}{2}\Delta t/t_L}$$

with similar equations for the other beams. Most broadband DVLs having piston transducers measure $f_0\Delta t$ using the phase of the demodulated signal autocorrelation function at or near the repeat lag t_L. The frequency f_0 is that of the local oscillator used for demodulation. The coefficient $\frac{c}{4f_0 t_L} = U_a$, known as the "ambiguity velocity," represents the velocity at which the phase is in radians, after correction for the non-linear denominator $1 - \frac{1}{2}\Delta t/t_L$. For narrowband DVLs, any lag can be used within the reciprocal of the signal bandwidth.

For phased array DVLs, it i s useful to multiply Δt by the receive frequency $f_r = f_w(1 + M_a)$ to calculate the phase, which is the same at all frequencies:

$$f_r\Delta t = 2f_w t_L M_a = t_L\Delta f = \frac{1}{2U_{a0}}\left(u\sin\theta_0 - w\cos\theta_J\left(\frac{\sin\theta_0}{\sin\theta_J}\right)\right)$$

where $U_{a0} = \frac{c_0}{4f_0 t_L} = \frac{d}{t_L}\sin\theta_0$ is the ambiguity velocity at a standard sound speed defined by the choice of stave spacing *d*, and θ_0 is the nominal beam Janus angle, typically 30°. Broadband phased array DVLs use the phase measured from the demodulated signal autocorrelation function at or near t_L to measure $f_r \Delta t = t_L \Delta f$. The vertical and horizontal velocity components can be separated by respectively adding and subtracting the measurements from opposite beams (see Section 2502). Although the sensitivity of the vertical velocity component to sound speed is typically 33% greater for phased arrays than it is for pistons, there is no sound speed sensitivity at all for the nominally-horizontal components parallel to the array face.

2507. References

Brokloff, N. A., (1994). *Matrix algorithm for Doppler sonar navigation.* Oceans '94. MTS/IEEE Conference Proceedings1994[3]:378-383. ©1994 IEEE. **Reprinted, with permission, from IEEE Proceedings**.

Brokloff, N. A., (1997) *Dead reckoning with an ADCP and current extrapolation.* Oceans '97. MTS/IEEE Conference Proceedings1997[2]:1411-1416. ©1997 IEEE. **Reprinted, with permission, from IEEE Proceedings**.

Kritz, J. and Howard M. J., (1969). *Channel Navigation and Docking of Supertankers*. NAVIGATION: Journal of the Institute of Navigation 16[1].

Laster, D. R., and Fagan J. W., (1965). *Exploratory Evaluation of Underwater Doppler Navigators.* U. S. Navy Marine Engineering Laboratory Evaluation.

Leroy, C. C., Robinson, S. P., and Goldsmith, M. J., (2008). *A New Equation for the Accurate Calculation of Sound Speed in all Oceans,"* J. Acoust. Soc. Am. 124[5]:2274-2783,

RD Instruments, (1996). *Acoustic Doppler Current Profiler, Principles of Operation A Practical Primer,* 2nd Edition for Broadband ADCPs, RD Instruments. **Used with permission from Teledyne RDI**.

CHAPTER 26

BATHYMETRIC NAVIGATION

BASIC TECHNIQUES OF BATHYMETRIC NAVIGATION

2600. Introduction

Until the arrival of this age of electronic technology, mariners relied solely on celestial navigation, paper charts and mechanical soundings techniques to navigate the world's oceans, Now, however, satellite technology, GNSS, and electronic positioning systems are capable of achieving sub-meter positioning accuracy, and vessels can even navigate using automated means alone. Satellite navigation has become so reliable that some maritime academic institutions have removed celestial navigation from their curriculum. Hydrographic offices, too, put the bulk of their efforts on producing electronic navigational charts in response to increasing industry demand for digital products and decreasing need for paper charts.

However, all things electronic are subject to the potential for failure, and as technology advances it is possible to become over-reliant on a single set of tools. As the maritime sector gradually acknowledges this vulnerability, there is renewed interest in traditional navigation techniques. For example, bathymetric navigation, which utilizes charted seafloor features and contours to help determine the position of a vessel, is once again being actively used in combination with celestial navigation or dead reckoning to provide a position solution in the absence of satellite navigation.

2601. Bathymetry and Bathymetric Navigation

Bathymetry is the science of mapping seafloor relief. Accurate bathymetric surveys help hydrographers identify submerged hazards to navigation, and allow oceanographers and geologists to better understand seafloor morphology and its impact on the ocean environment.

The principle behind bathymetric navigation is simple. When a mariner knows a vessel's last position with reasonable confidence, and has nautical charts that depict soundings, seafloor features and depth curves, then the mariner can use those charted bathymetric features to refine their assumed position.

For example, if a mariner were to be navigating in the vicinity of a charted seamount, and there exists a measure of uncertainty regarding the accuracy of their positioning fix, the mariner can validate the vessel's position by comparing echo sounder readings with the assumed position while sailing over the submerged seamount.

The usefulness of this technique is dependent up on several factors: the accuracy of the chart, the reliability of the last position fix, and the capabilities of the vessel's echo sounder.

The National Oceanic and Atmospheric Administration (NOAA) produces a series of bathymetric maps of the waters adjacent to portions of the coast of the United States. These maps extend seaward somewhat beyond the 100-fathom curve and show the contour of the bottom in considerable detail. Such maps can be of great assistance in fixing position by means of the depth finder. The maps are available online and can be accessed via the link provided in Figure 2601.

Figure 2601. NOAA - U.S. Bathymetric Maps https://www.ngdc.noaa.gov/mgg/bathymetry/maps/nos_intro.html

2602. Nautical Charts

Nautical charts are compiled from a combination of bathymetric surveys, soundings collected using a variety of historical techniques, and depths reported by mariners. Although it may be tempting to assume that where there are soundings on a chart, the area has been thoroughly surveyed, this can be a dangerous presumption. It is not an over-generalization to say that most of the world's oceans are still unsurveyed.

The ocean is vast, and although technology is always improving, modern hydrographic surveys are still expensive and time-consuming. In many areas, charted soundings are compiled from pre-1900 lead line surveys, or from 20th century singlebeam echo sounder surveys (see chapter on Hydrography for more information about survey techniques). These survey methods do not provide full sea floor coverage, and could miss significant seafloor features.

In addition, much of the depth information in nautical charts was collected before modern satellite positioning techniques were available. This introduces a degree of uncertainty in the location of some charted depths. Mariners should always consult the chart's source diagram to determine the type and age of data that was used to compile soundings for any specific region of the chart, and always use the best-scale, most current product available for bathymetric navigation.

2603. Positioning

When vessels navigate using GNSS, mariners can usually be confident in the accuracy of their position fix. There may be times when the quality of the satellite signal degrades due to poor geometry overhead, or steep terrain that blocks signals or causes multipath (such as in narrow fjords), but generally, satellite navigation is reliable.

If, however, a navigator is unable to use satellite positioning systems, they will need to rely on other methods, such as celestial navigation or dead reckoning (or a combination of the two). With accurate celestial navigation measurements, obtained through practice and skill, mariners can determine their position with a reasonable degree of accuracy (see Part 3 on Celestial Navigation for more information).

When persistent inclement weather or overcast skies prevent mariners from taking star sights or sun fixes, then mariners must resort to dead reckoning. Dead reckoning measures the amount of time elapsed since the last known position fix, the speed of the vessel, its ordered course, and known set and drift to derive an estimate of the vessel's location. The reliability of dead reckoning degrades with time, as the compilation of slight errors compound.

Because there is almost always some uncertainty in position fixes when using celestial navigation and dead reckoning, mariners find it useful to better determine their location using bathymetric navigation.

2604. Echo Sounders

Most modern vessels, from small pleasure boats to large cargo ships, have some type of electronic echo sounder mounted on the keel. These echo sounders measure the time it takes for a pulse of sound to travel to the seafloor and return to the transducer. This measurement of time is then electronically translated into a depth measurement, and the navigator of the vessel uses the depth measurement, in tandem with a nautical chart, to determine a safe course.

Echo sounders vary widely in design and capability. Many models collect depth information about only a narrow cone of water beneath the vessel. These may be referred to as singlebeam SONAR, fathometers, or depth finders. Some higher-end models emit many beams of sound, in a wide swath below, or in front of the vessel. These designs are called multibeam systems, and are capable of generating a very high-resolution three-dimensional SONAR image of the seafloor or approaching obstacles (see chapter on Hydrography for more information about echo sounder designs).

All echo sounders are limited to a certain depth operating range, which is constrained by the power and frequency of the system. In general, shallow-water echo sounders will be higher-frequency, and require less power. Deep-water echo sounders will be lower-frequency, and require more power. Echo sounders are capable of detecting smaller features in shallow water, and their resolution degrades with depth pulses.

Before attempting bathymetric navigation, mariners should determine what kind of echo sounder they have on board. This will help them identify the capabilities and limitations of their system. For instance, with a singlebeam echo sounder, the mariner would be able to compare charted soundings to depth measurements, and follow patterns in depth trends that correspond to charted contours. With a multibeam echo sounder, mariners might be able to generate very high-resolution SONAR maps of the seafloor. While this could help the mariner identify charted features, it is also possible to collect higher-resolution data than depicted on the chart!

Regardless the type of echo sounder used, it is likely that, at some point, vessels will collect depth information in transit where there is no charted data. This information can be valuable for oceanographic studies, hydrographic purposes, and the greater public good. For those who will donate their data, the International Hydrographic Organization (IHO) supports a crowdsourced bathymetry initiative that encourages mariners to connect data loggers to their echo sounders, and submit the collected information to a public database. For more information, See the link provided in Figure 2604 or visit www.iho.int.

It is also possible to collect depth information without an echo sounder in shallow water, using a lead line or sounding pole. These techniques are not widely used today, as they are time-intensive, and require stopping the vessel and manually deploying a weighted line or long pole over the side. However, they are reliable methods of obtaining depth information, and in theory can be used to compare charted depths with measured soundings.

Figure 2604. IHO World Bathymetry
https://www.iho.int/srv1/index.php?option=com_content&view=article&id=300&Itemid=744&lang=en

2605. Sound Velocity

Mariners should be aware that the depth measurements collected by echo sounders will vary based on the temperature, salinity, and depth of the local water column.

Each of these factors has an impact on the speed and path of sound waves through water. In general, sound travels faster through warm water, saltier water, and deeper (denser) water.

Because echo sounders generate a depth measurement based on the two-way travel time of a sonar beam, differences in water column composition can generate variations in depth measurements. For example, if a vessel travels through a coastal area where a freshwater river runs into the sea, the speed of sound will slow, and the depth measurement may be slightly incorrect.

Some echo sounders have a surface sound velocimeter installed on the hull to at least partially correct for these local water column variations, others do not. Before attempting bathymetric navigation, one should determine whether or not the echo sounder is equipped with integrated sound velocity corrections.

2606. Other Considerations

Sound waves from an echo sounder will reflect off of anything in the water column, and may even penetrate the surface layer of soft or muddy bottom sediment, and reflect off of the underlying bedrock. Fish, bubbles (from marine life or another ship's wake), dense layers of plankton or marine life, vegetation, variations in salinity, and marine mammals can all cause 'false bottom' readings, or obscure the true bottom. Mariners should be aware of these exceptions when using fathometers to identify seafloor features.

BATHYMETRIC NAVIGATION USING FEATURE RECOGNITION

2607. The Basics

Once the mariner has obtained an initial position fix, determined a rough assessment of the age and accuracy of the information used to compile their chart, and identified the type of echo sounder that is mounted in their vessel, they are ready to use bathymetric information to verify their position.

For the purposes of this chapter, we will assume that the mariner is using hardcopy charts and non-satellite positioning methods, and is navigating out of sight of land. Note that if the mariner is within sight of land, it may be easier and more accurate to verify position by simply taking bearings on features on shore, rather than by comparing bathymetric features to echo sounder readings.

If the mariner is beyond the sight of land, they should choose a prominent charted seafloor feature or set of features that fall near their estimated position, and are at a depth that permits the vessel to safely transit across it. The features should be unique enough to be readily detectable (such as seamounts, ridges or canyons), but should not be complex or 'clumped' features, as they will be more difficult to distinguish and use for positioning. The feature should have enough relief to be easily distinguishable from the surrounding seafloor. If the seafloor is flat and featureless bathymetric navigation will not work, as all depths will appear relatively uniform.

Ideally, the mariner should select a feature that falls within an area recently surveyed for hydrographic purposes (as indicated on the source diagram); those features are likely to be more accurately and fully represented than features from other sources. For example, if an area was fully surveyed using multibeam sonar, a cartographer knows exactly where the 50m contour is located. If an area was surveyed with isolated lead line soundings, the cartographer has to make an educated guess about where to draw the 50m contour between soundings.

If there are no recent hydrographic surveys in the area, the mariner should simply choose a feature that is prominent, and is not listed as 'reported,' 'position doubtful,' etc. Some features that may be useful for bathymetric navigation are:

- Seamounts (isolated or in small groups)
- Ridges
- Canyons
- Plateaus

Once the mariner has selected the feature or set of features, they should plot a course across the feature (or features), reduce vessel speed so that the echo sounder return provides a clear and easily readable bottom trace, and then transit over the feature, attempting to intersect it in a direction that provides the clearest delineation of its location.

If the mariner is using a ridge or a canyon to verify position, the vessel should cut across the feature in a direction that is perpendicular to its main (long) axis. The echo sounder will provide a clear profile of the sides of the feature, and the positions and depths can then be compared to the contours or depths on the chart.

If the mariner is using a plateau or seamount to verify a position fix, the vessel may need to make one or more passes over the feature, which each line offset at a different angle from the last, to ensure that they have located the feature, and not just clipped the edge. If the area is poorly surveyed, caution should be exercised when doing this, to prevent the vessel from encountering a portion of the seamount that is shoaler than charted.

Whenever possible, it is best to transit more than one feature in a row, as locating multiple features that area aligned at a single known bearing provides the most accurate position verification

2608. Additional Considerations

When using bathymetric features to validate a position fix, it is important to note that the vessel's last known position should be reasonably reliable. If there are gross errors in dead reckoning

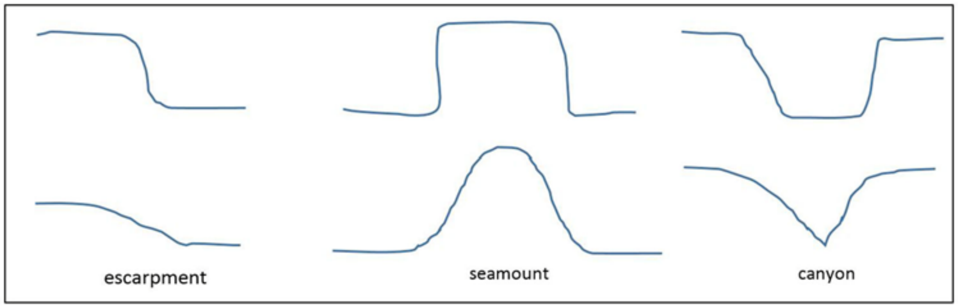

Figure 2608. Bottom features (top row) compared with measured echogram (bottom row).

measurements or celestial navigation calculations, bathymetric positioning will be of little value, as the mariner will be searching in the wrong area to begin with. Bathymetric navigation should be used as a refinement of last known position, not the sole positioning determination method.

In addition, it should be noted that the sonic footprint of some singlebeam echo sounders can make the sides of submerged features appear more rounded than they actually are (Figure 2608). This should be taken into account when comparing charted contours to echo sounder traces.

2609. Other Positioning Methods

Profile-matching. If a vessel is operating in an area where there are no significant features, but the charted contours are varied enough to assist with position identification, a vessel could transit back and forth across the area in a grid pattern, recording the depth profiles with each pass, and then correlate those sequential profiles to the charted contours.

Profile-matching is more time-consuming than the feature recognition method, but if executed properly, and where good comparison contour data is available, this could yield very accurate positioning information. If the vessel has a multibeam echosounder on board, this process would produce a fairly high-resolution map of the seafloor.

Contour Advancement. As with profile-matching, contour advancement does not require that significant features be present, but it is desirable to transit across a gently sloping area with slopes that are greater than one degree, but no more than four or five degrees. The area should also be well-charted, with moderately reliable contours.

To use the contour advancement technique to verify a position fix, a vessel must transit across an area at a constant bearing and speed, in line with the direction of a known slope. When the (singlebeam) echo sounder depth matches a charted contour depth, the navigator knows that the ship is somewhere on that charted depth contour - but precisely where is unknown. This first contour becomes the 'reference' contour, and is traced onto a transparent overlay that will be shifted (or advanced) on the chart as new contour depths are collected.

When the echo sounder indicates that the vessel has reached the next charted contour depth, the navigator moves the reference contour overlay forward to the new estimated position on the chart. The distance that the contour is advanced is determined by measuring the time it took to travel between observed contour soundings, and multiplying that time by the vessel's constant speed.

Advancing the reference contour has the effect of moving every possibility of the ship's starting location on that first contour visually into the vicinity of the next contour (basically, offsetting every point on the first contour by the distance covered, without having to manually draw all of those infinite offset points). If executed accurately, the intersection of the advanced contour (i.e. the first contour, offset by the distance covered) and the next charted contour will note the true location of the ship, provided that there is only one intersection.

Multiple intersections of the reference and charted contours means that there is more than one possible position. The mariner must then continue the contour advancement process to determine which candidate is the true track.

In the Figure 2609, the solid lines are charted contours, and the dashed lines are the advancement of the initial reference contour. The ship's estimated track (which the navigator plots on the overlay, and could have started anywhere on the reference contour) is the dashed line perpendicular to the contours. The time between echo sounder observations of charted contour depths is annotated on each track. The ship's true position is shown on the right; it identifies the areas where the vessel crossed each of the contours, after the advanced contour indicated the points of intersection.

Typical accuracy for contour advancement is approximately one-quarter of the contour spacing of the chart.

Basic Rules of Thumb for Contour Advancing are as follows:

- An accurate bathymetric chart of the region being traversed is required.
- Slopes should be between 1° to 4° (no more than 5°), and they should be varying; use of areas with constant slopes could result in intersections which are along lines, not at points, and so would not reveal precise location.

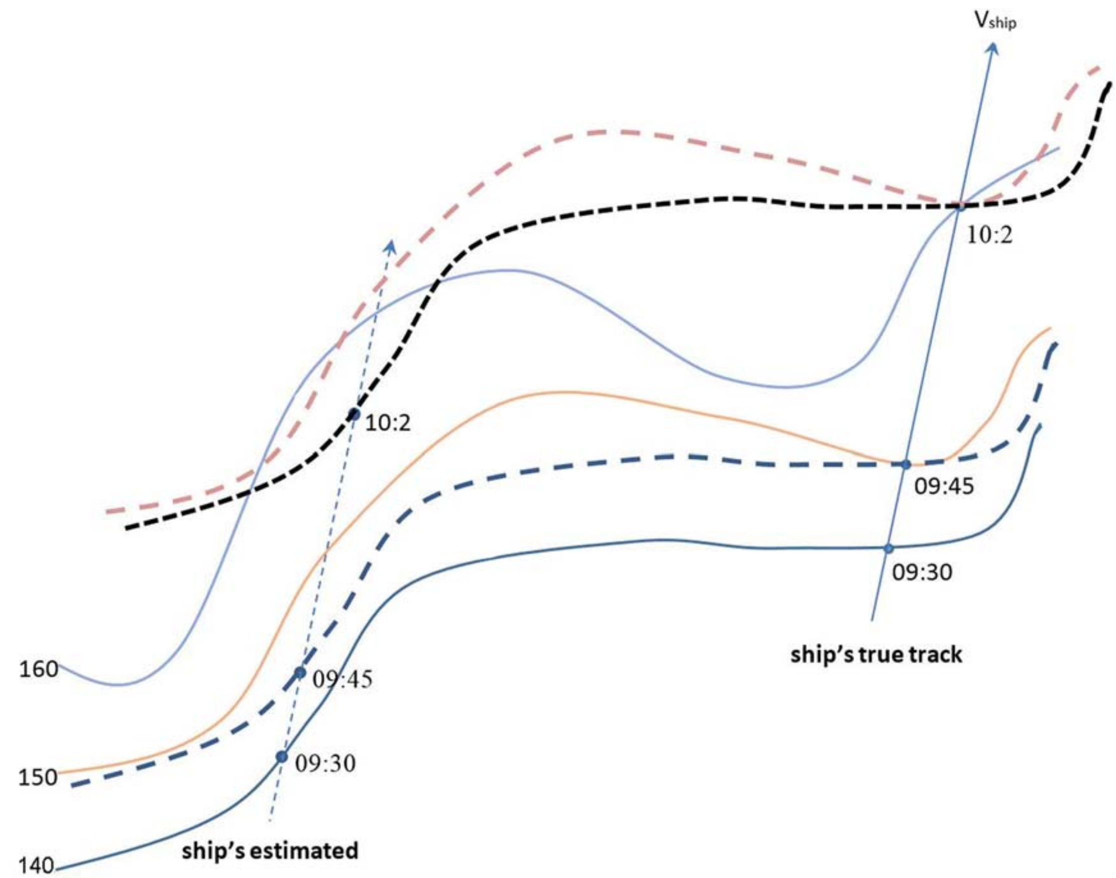

Figure 2609. The technique of contour advancing is illustrated in this figure. The isobaths shown in Figure 4 as solid lines are the contour lines on the chart; all dashed isobaths are results of contour advancement of the chart isobaths. Shown here for convenience is the true ship's position track, which is unknown to the navigator. The time of passage of the charted isobaths is also shown on the true track for convenience, more importantly, they are shown on the ship's estimated position track, which the navigator is plotting on the chart. Initially, the navigator traces the 140 isobath onto the overlay at 9:30 and establishes a reference point anywhere on the traced 140 isobath. Also note that this procedure can be performed after the fact if the times of passage, their charted depth, and the ship's velocity have been recorded for later use. When the next charted isobath, 150, is passed at 9:45, the navigator advances the overlay to the new estimated position. The advanced 140 isobath must intersect the charted 150 isobath at the ship's true location. If this is the only place of intersection of these two isobaths, the fix can be established at this time; the location of the intersection of the two isobath's is the ship's true position at 9:45. But there may be multiple locations of intersection, one of these is hinted at on the far right side of the displayed contours and perhaps one slightly to the left of the ship's estimated position. The advancement can then continue to the next charted isobath, 160, to help resolve the true location. In that case, the advanced 140 and 150 isobaths hint at possibly intersecting again at the far right, but the charted 160 isobath diverges from them there, and the location slightly to the left of the estimated ship's track doesn't show a strong three-way intersection like at the point on the true track at the point labeled 10:20, showing that the point labeled 10:20 on the true track would be the ship's true position at that time. The intersections may form a triangle instead of a point due to errors, the smaller the triangle, the better the confidence in the fix; or perhaps additional contours can be advanced to help resolve the fix if the error triangle is too large. Typical accuracy is on the order of ±100 yards, or about one-quarter of the line spacing of the chart.

- Contour advancing is made easier by using the largest scale chart available, assuming the area is not absolutely flat. A given chart may not show any slope for a given area, but the area may show some relief on a larger chart.

2610. Line of Sounding Technique

Recovering a position fix using the line-of-soundings technique is similar to contour advancement, but usually requires collecting more observed depths to obtain an accurate fix. A vessel using a singlebeam echo sounder runs a single straight line

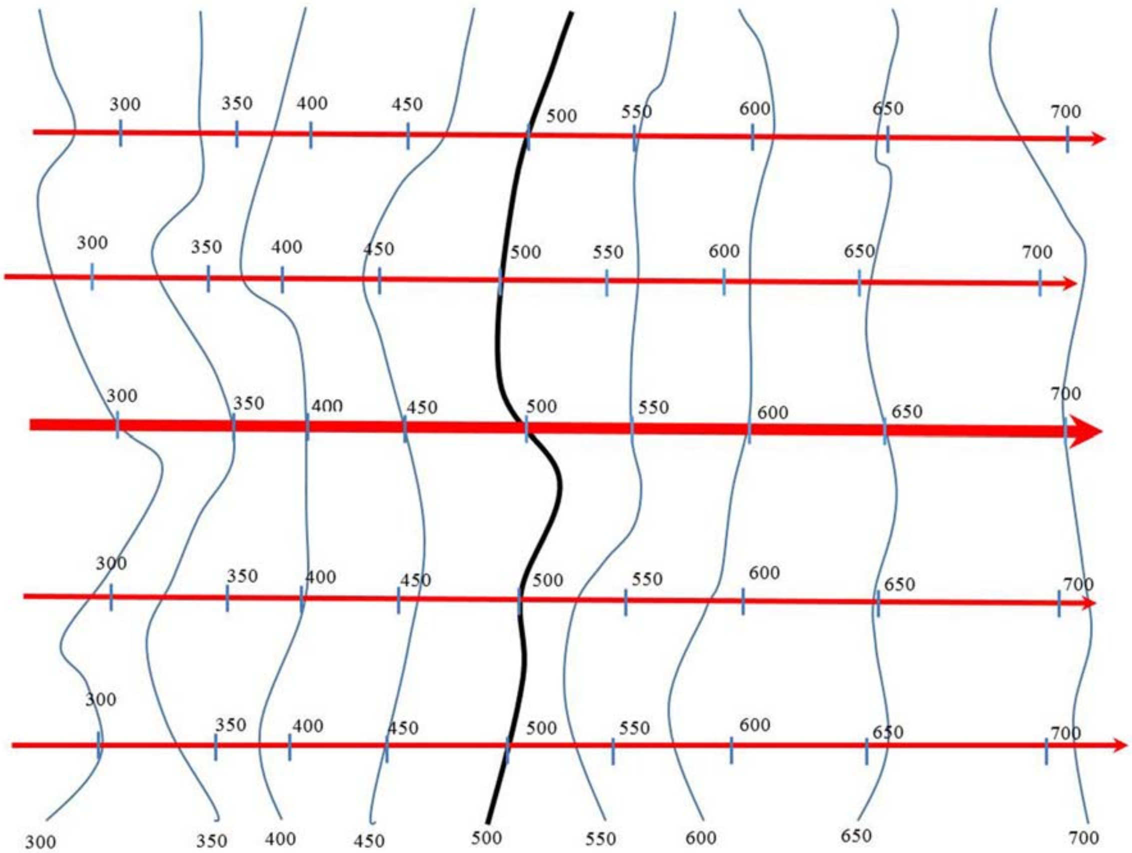

Figure 2610. Line of soundings technique. Image courtesy of Johns Hopkins University - Applied Physics Laboratory.

over a charted area at a constant bearing and speed, and the sounding values that correspond to charted contours are plotted onto a trackline on a clear chart overlay. The line is then moved across the charted contours, until the plotted soundings match up with the charted contour interval. This provides a position fix. If a vessel is using a multibeam echo sounder, the continuous swath of seafloor data can also be compared to the charted contours, to identify matching patterns with higher fidelity.

In Figure 2610, the red lines represent the singlebeam echo sounder trackline of plotted overlay soundings. The navigator moved this trackline across the charted contours, using the 500m contour as a central reference guide, until they found a match (the trackline in the center of the chart). Like other forms of bathymetric navigation, this method would not work in a very flat area, since the trackline would appear to match the depths in many directions.

2611. Side Echo Technique

The side-echo technique is useful for determining position when traversing seamounts. For this method, the vessel must conduct at least two transit lines across the seamount, each of constant bearing and speed, offset from each other at right angles. The depth trend on each line indicates the quadrant location of the shoalest (shallowest) point of the seamount, relative to the intersection of the transit lines.

The navigator should plan the initial transit line so that it approaches the seamount from a distance of at least 20 or 30 nautical miles. In deep water, this distance will help the navigator identify changes in seafloor relief and will help prevent missing the feature (the track should capture at least the base of a large feature, even if the shoalest point is missed). The vessel should maintain a constant course while approaching the seamount. If the vessel is using a singlebeam echosounder, the navigator should plot the depths at regular intervals (e.g. once per minute) while crossing the feature. The minimum depth should be noted and marked on the trackline.

Once the initial transit has crossed the feature, the vessel should run another transit line, exactly perpendicular to the first. The navigator should again plot the depths periodically, and annotate the point of least depth. If a line is then drawn between the shallowest point on each line, the point where they intersect indicates the quadrant of the shallowest point on the seamount. If the vessel is using a multibeam sonar, the overlapping swaths from each line should show a clear depth trend towards one quadrant, and could even capture the shoalest point of the feature.

Once the approximate location of the shallowest point of the seamount is determined, that location can be compared to the charted minimum depth, to provide a position location for the vessel. Additional lines, offset to the first two, could help to more precisely locate the shoalest points. However, it is important to note that the charted minimum depth of the seamount could be wrong; previous surveys or reports may have only crossed over one side of the seamount, instead of directly over the shallowest part, or the horizontal positioning methods used at the time may have been inaccurate, and the seamount's location could be slightly incorrect (see Figure 2611b). Whenever possible, the mariner should try to select a feature that comes from a reliable source, such as a hydrographic survey.

If a mariner finds that the actual depth of the seamount is shallower than the charted least depth, that information should be reported to NGA's Maritime Safety Office as soon as possible (see link in Figure 2611a), so that the chart can be updated.

Figure 2611a. Link to NGA's Maritime Safety Office - Contact Information. https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_st=&pageLabel=msi_contact_info

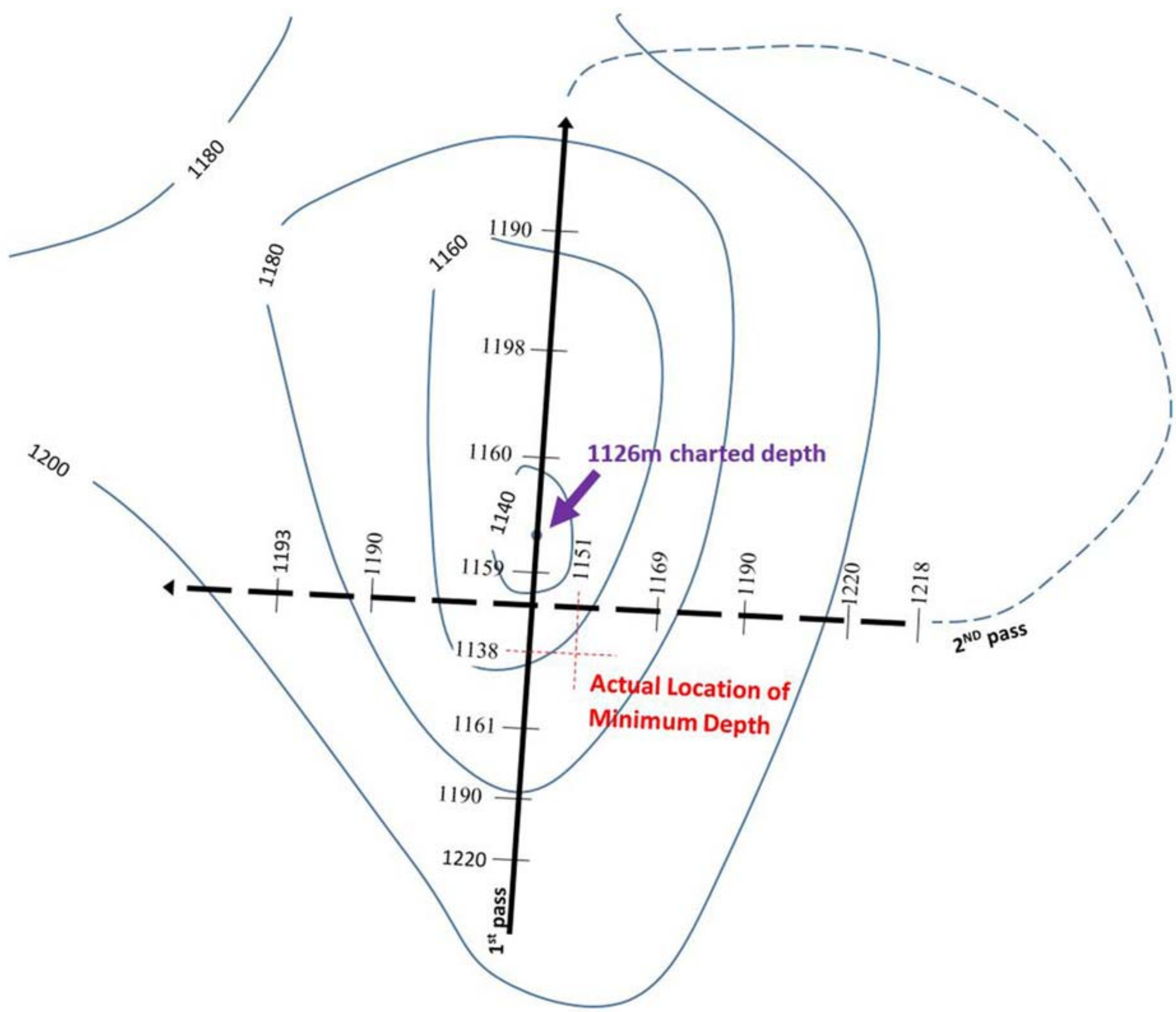

Figure 2611b. Side-echo bathymetric navigation. This image is provided courtesy of Johns Hopkins University- Applied Physics Laboratory.

2612. Computerized Techniques

Automated programs exist that can incorporate singlebeam or multibeam SONAR data, along with the speed and course of the vessel, and compare that data directly to digital features and chart contours. These programs can provide an approximate position fix without the need to manually overlay and plot soundings.

2613. References

Cohen, P M., (1970). *Bathymetric Navigation and Charting.* U.S. Naval Institute Press, Annapolis, MD. **Sections reprinted with permission.**

Cutler*, T J., (2003). Dutton's Nautical Navigation,* 15th Edition. U.S. Naval Institute Press, Annapolis, MD. **Sections reprinted with permission.**