PILOTING

CHAPTER 7

SHORT RANGE AIDS TO NAVIGATION

DEFINING SHORT RANGE AIDS TO NAVIGATION

700. Terms and Definitions

A short range/visual Aids to Navigation (ATON) system is a series of interacting external reference devices intended to collectively provide sufficient and timely information with which to safely navigate within and through a waterway when used in conjunction with updated nautical charts. The system includes all navigational devices within visual, audio, or radar range of the mariner. Specifically, these aids to navigation encompass buoys (lighted and unlighted), beacons (lighthouses, lights, ranges, leading lights and daybeacons), sound signals, Radar Beacons (RACON) and Automatic Identification System - Aids to Navigation (AIS-ATON). See Section 2311 (Aids to Radar Navigation) for more information on RACONs. See Section 3024 for more information on AIS-ATON.

This chapter describes the U.S. Aids to Navigation System (USATONS) as well as the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) Maritime Buoyage System (MBS).

Except for minor differences in the U.S. Intracoastal Waterway and Western Rivers (Mississippi River) System, the USATONS is predominately a **lateral** system consistent with Region B requirements of the IALA MBS (Region A for U.S. possessions west of the International Date Line and south of 10 degrees north latitude).

The United States Coast Guard is responsible for establishing, maintaining, and operating marine aids to navigation in the navigable waters of the United States, its territories, and possessions. As such the Coast Guard establishes, maintains and operates lighted and unlighted buoys and beacons (lighthouses, lights, ranges, leading lights and daybeacons), sound signals, AIS-ATON and RACONs. In Addition, the Coast Guard has administrative control over privately owned navigation aids to navigation systems.

BUOYS

701. Definitions and Types

Buoys are floating aids to navigation, anchored at specific locations via chain or synthetic line attached to concrete or cast-steel sinkers. They are used to mark channel limits, indicate isolated dangers, shoals, and obstructions, and to warn the mariner of hazards or dangers. Buoys are typically deployed in locations where beacons would be impractical or cost-prohibited due to waterway geographic configuration and/or environmental conditions, such as water depth, prevailing wind direction and fetch, current, etc. The color, shape, number, topmark, light, and sound characteristics of buoys provide specific marine safety information to mariners.

Buoys are constructed of resilient materials such as non-ferrous steel or plastics such as ionomer polymer plastics (or combination), having structures designed to meet specific environmental factors and purpose. They are classified either lighted or unlighted; either of which can be augmented with sound signals. Unlighted and smaller lighted buoys are shape significant, indicating the type of **mark** the buoy is portraying. There are many different buoy sizes, each designed to meet specific environmental conditions, mariner need, and signal requirements. Larger buoys are typically used in off-shore and coastal environments, while smaller buoys are deployed in less exposed settings such as inshore and inland waterways.

Lighted buoys are configured with three general components - the buoy hull, which rides above and below the sea surface; the counterweight, which is completely below the water surface and is designed to keep the buoy upright; and the buoy superstructure - also known as the buoy cage (see Figure 701a). Most lighted buoys are referred to as Pillar Buoys, because their superstructure is affixed to a broader circular base, i.e. the buoy hull. Lighted buoy hulls and superstructures can also be constructed with non-ferrous materials, such as ionomer foam, attached to a steel counterweight. Most lighted buoys deployed by the Coast Guard are equipped with Light Emitting Diodes (LED) lanterns, many of which contain the power system and LED within the lantern housing and are referred to as self-contained LED lanterns. Batteries for lighted buoys without self-contained LED lanterns are secured in watertight pockets in the buoy hull or in watertight boxes mounted on the buoy hull. All lighted buoys are equipped with some form of enhanced radar reflector built into or attached to the buoy superstructure. See Figure 701b.

The largest of the U.S. Coast Guard lighted buoys has

Figure 701a. Buoy with counterweight showing.

Figure 701b. Small lighted buoy.

a focal plane of 20+ feet, a radar and nominal visual range of 4 and 3.2 nautical miles respectively in calm seas and clear visibility, and can be moored using conventional buoy chain in depths up to 190 feet of water; greater water depths when moored with synthetic line.

Unlighted buoys are typically classified by their shape (can, nun, or special purpose). The range in size from a 1st class steel buoy weighing 6,000 pounds with a 5-3/4 foot freeboard to small plastic and ionomer foam buoys, weighing 65 pounds with a one foot freeboard. See Figure 701c and Figure 701d.

Figure 701c. Can buoy.

Figure 701d. Nun buoy.

A variety of **special purpose buoys** are owned by other governmental organizations, such as the St. Lawrence

Seaway Development Corporation (SLDC), National Oceanic and Atmospheric Administration (NOAA), and the Department of Defense. These buoys are usually navigational marks or data collection buoys with traditional round, boat-shaped, or discus-shaped hulls.

A special class of buoy, the **Ocean Data Acquisition System (ODAS)** buoy, is moored or floats free in offshore waters. Positions are promulgated through radio warnings. These buoys are generally not large enough to cause damage to a large vessel in an **allision**, but should be given a wide berth regardless, as any loss would almost certainly result in the interruption of valuable scientific experiments. They are generally bright orange or yellow in color, with vertical stripes on moored buoys and horizontal bands on free-floating ones, and have a strobe light for night visibility.

702. Buoy Moorings

Navigation buoys require moorings to hold them in position. Typically the mooring consists of chain and a large concrete or cast steel sinker. Because buoys are subjected to waves, wind and tides, the moorings must be deployed with chain lengths several times greater than the water depth, referred to as the scope of chain, typically about 3 times the water depth. The length of the mooring chain defines a watch circle within which the buoy can be expected to swing around its sinker. This is the reason charted buoy symbols have a “position approximate” circle to indicate its assigned position, whereas a light position is shown by a dot at the exact location. Actual watch circles do not necessarily coincide with the “position approximate” circles which represent them. The below formula is used to calculate the buoy watch circle:

$$\text{Watch Circle Radius} = \sqrt{\text{Water Depth}^2 \quad \text{Chain Length}^2}$$

Buoys are assigned to specific geographic positions calculated to within a thousandth of a second, known as the assigned position (AP). The Coast Guard employs the Global Positioning System (GPS) and other methods to place a buoy as close to the AP as reasonably possible and to verify that it is anchored within positioning tolerances. However, placing a buoy at a specific geographic location is secondary to ensuring that the actual location of the buoy best marks the waterway and serves the purpose for which it was intended. Also, a buoy's AP actually indicates the assigned position of the buoy's sinker, which coupled with the buoy's watch circle results in the buoy rarely positioned at its exact assigned position.

703. Lights on Buoys

As mentioned in Section 701, buoy light signals in the USATONS, with rare exception, are exhibited with LEDs. They are powered with secondary lead-acid or similar batteries slow-charged via solar panels. The power configuration is designed to accommodate the specific light characteristic and intensity settings for specific geographic locations. For example, a buoy light in Florida, because of greater year-round sunlight, requires a smaller solar power configuration than a buoy light with the same characteristic in Alaska.

704. Audible Signals on Buoys

Sound buoys whether lighted or unlighted are configured much the same as lighted buoys. They can be outfitted with either a bell, gong, whistle, or electronic horn. All but the electronic horn produce sound from the buoy movement as influenced by the restless motion of the sea. Electronic horns, rare on buoys, are powered via electricity produced by batteries. Since bell, gong, and whistle buoys depend on the motion of the sea to produce the sound signal, these types of buoys are deployed in exposed and semi-exposed locations. Horn buoys are deployed in protected and semi-protected locations.

The buoy **bell** is externally mounted on a heavy steel flange, which is permanently affixed to the top center of the buoy hull. The bell produces sound when its struck by one of four (4) tappers that are affixed to the buoy cage and swing freely with the buoy motion. Bells employed by the Coast Guard come in 85 and 225 pound sizes. Gongs are similarly mounted as bells but in sets of three gongs. Each of which gives a distinct tone when struck by the tapper. The three tappers, each of different length to accommodate the gong position, are attached to the buoy cage in the same way as the bell tappers.

Figure 704. Lighted bell buoy.

Whistle buoys make a loud moaning sound as the buoy rises and falls in the sea swells. As the buoy raises air is drawn into the hollow counterweight tube, which as the buoy falls with the swell is forced through the whistle valve mounted atop the buoy hull emitting the lonely mournful sound of the whistle buoy. Electronic horns are suspended from one of the buoy superstructure cross-members and are powered via a solar panel charged battery power configuration.

Audible signals are intended to provide marine safety information during periods of restricted visibility. Due to the inability of the human ear to accurately judge the direction of a sound source, they are only used to warn mariners of the proximity of a hazard or obstruction. Therefore, although sound signals are valuable, mariners should NOT exclusively rely on them to navigate.

705. Western Rivers Buoys

Buoys used to mark the Mississippi River System are primarily unlighted and are consistent with the following variables:

1. Can buoys are a slightly darker shade of green to improve conspicuity.
2. Unlighted buoys are not numbered.
3. Western River Buoys are not assigned positions.
4. Western River Buoys are not listed in the Light List.

Due to continuously shifting shoals and water levels, unlighted buoys in the Western Rivers are frequently moved to best mark the waterway. The Coast Guard provides buoy positions to the U.S. Army Corps of Engineers periodically, which in turn provides a buoy layer for their Inland Electronic Charts. The few lighted buoys deployed in the Western Rivers are consistent with IALA Region B without revision. See Figure 705 for an image of a Coast Guard River Buoy Tender.

Figure 705. USCG river buoy tender.

706. Seasonal Buoys

Many lighted buoy are deployed regions that are subject to severe winter icing conditions; namely the U.S East Coast (north of the Chesapeake Bay Entrance), the Great Lakes, and section of Alaska. Ice can cause significant damage to lighted buoys. For example, moving ice can temporarily cause a buoy to heel over, submerge, and/or drag off station, destroying its light signal equipment in the process. Submerged and off-station buoys often pose a hazard to navigation. Figure 706 depicts the USCG recovering an iced damaged buoy.

Figure 706. USCG recovering ice damaged buoys.

To mitigate this risk, the Coast Guard replaces many lighted buoys with either unlighted buoys or specially constructed lighted buoys that are better able to survive winter ice conditions. These lighted ice buoys do not meet the same operational characteristics as the “approved lighted buoys they replace, so they're replaced again in the spring with authorized lighted buoys. The specific seasonal buoy relief schedules are contained in the applicable Light Lists (column 8).

707. Buoys Marking Wrecks

Buoys used to mark wrecks typically are not placed directly over the wreck it is intended to mark for two primary reasons: First, Coast Guard ATON maintenance units could be hazarded while approaching to perform maintenance on the buoy, especially when the buoy marks a shallow wreck. Secondly, there is a risk for buoy moorings to foul on the wreck. Therefore, a wreck buoy is usually placed as closely as possible on the seaward or channel ward side of a wreck.

In some situations more than one buoy may be deployed to mark a wreck to avoid possible confusion as to the actual location of the wreck. The *Local Notice to Mariners* should be consulted concerning details regarding the placement of wreck buoys on individual wrecks. The Notice will often define the particulars of the wreck and activities that may be in progress to clear the waterway of the wreck. Sunken wrecks may also move away from the wreck buoy(s) by storms, currents, freshets, or other causes.

Wreck buoys are required to be placed by the owner of the wreck, but they may be placed by the Coast Guard when the owner cannot comply with this requirement. Generally, privately owned aids to navigation are not as reliable as Coast Guard maintained aids to navigation.

Unless a waiver is granted by the responsible Coast Guard District Commander, buoys marking wrecks are required to be lighted and must conform to the U.S. buoyage marking system. They are also required to be marked with the letters "WR" before the buoy lateral number.

The charted depiction of wreck buoys are normally offset from the buoy's actual assigned position so that wreck and buoy symbols do not overlap. Only on the largest scale chart will the assigned position be actually depicted on the chart.

708. Large Navigational Buoys

Large Navigational Buoys (LNB), referred to as Large Automated Navigation Buoys (LANBY) by some international aids to navigation authorities, are major floating aids to navigation sometimes deployed in international waters. They may carry one or more RACON, AIS-ATON, sound, light, and in some cases radio beacon signals. The U. S. Coast Guard no longer deploys these buoys.

709. Buoy Maintenance

With the exception of private aids to navigation and certain U.S. Armed Forces maintained ATON, the Coast Guard is responsible for maintaining the buoys and beacons of the USATONS.

Scheduled unit level or on-scene maintenance of buoys consists of inspecting and replacing if necessary the buoy numbers and reflective tape, light, power, sound, and buoy mooring components. Actions may include cleaning, inspecting, and repairing as necessary the buoy hull, superstructure and counterweight, and verifying that the buoy is within tolerance of its assigned position or that it best marks the waterway and serves the purpose for which

Figure 709. USCG removing marine growth from a buoy.

Periodically, buoys are relieved with a buoy of equivalent type and removed from its AP to undergo depot level maintenance at a Coast Guard or Commercial facility.

Unscheduled maintenance is performed whenever a buoy is discrepant, i.e. not exhibiting the proper characteristics as advertised in the appropriate volume of the Light List.

710. Buoy Limitations

Even though the Coast Guard operates a multi-layered ATON maintenance scheme, buoys cannot be relied on to maintain their precise assigned positions permanently or to display their advertised signal characteristics. Buoys are subjected to a variety of hazards including severe weather, equipment failures, mooring casualties, and allisions. Even in clear weather there is a risk of vessels alliding with a buoy. If struck head-on, a large buoy can inflict severe damage to a vessel, and can sink smaller vessels.

Reduced visibility caused by weather, smoke, or extensive background lighting can increase the risks of alliding with a buoy. Many buoys that reported as missing to the Coast Guard were actually run over and sunk. Tugs and towboats towing or pushing barges run a higher risk of al-

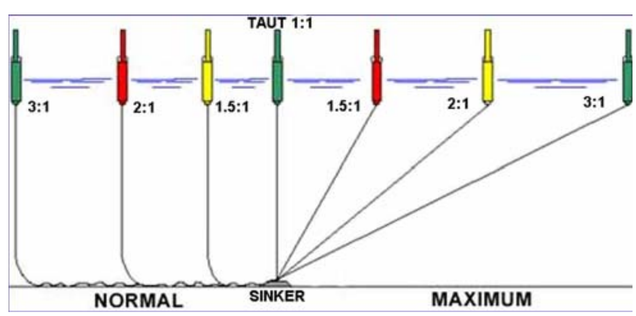


Figure 710. Watch circle radius.

liding with buoys, especially in moderate or rough sea conditions. Mariner must report any allision with a buoy to the nearest Coast Guard unit. Failure to do so may cause the next vessel to miss a channel or hit an obstruction marked by a buoy; it can also lead to fines and legal liability.

Buoy symbols depicted on charts indicate the approximate position of the sinker which secures the buoy to the seabed. As mentioned in Section 702, the buoy is always moving and is rarely directly over its sinker (see Figure 710). Therefore, buoys should never be used for precision navigation. Nor should they be passed close aboard, as doing so risks allision with a yawing buoy or possibly striking the obstruction that the buoy marks.

To ensure the most accurate aids to navigation system, mariners are urged to report discrepancies to the appropriate Coast Guard authority.

BEACONS

711. Definition and Description

A **beacon** is a stationary, short range visual aid to navigation that is fixed to terra firma or the seabed via a foundation, as such they are often referred to as **fixed aids** to navigation. They are lighted, unlighted, or audible. They range in size, type, and signal capability from large lighthouses to single-pile **daybeacons** to onshore sound signals. Beacon types include: Lighthouses, lights, ranges, leading lights, daybeacons, sound signals, RACONs and AIS-ATON.

712. Major and Minor Lights

Operationally, lighthouses and lights are classified as either **major** or **minor** lights. A **major light** displays a high-intensity light signal with a nominal range of at least 10-nautical miles (statute miles on the Great Lakes). They can have lateral significance but are typically used as primary seacoast, coastal navigation, or harbor entrance lights, and are rarely assigned to a lateral system. **Minor lights** display lower intensity light signals with nominal ranges of less than 10-nautical miles (statute miles on the Great Lakes). They are established in harbors, along channels, waterways, and rivers. They are typically assigned a numbering, coloring, and light scheme consistent with the appropriate lateral buoyage system.

Both major and minor lights display their light signal from a variety of ATON structures, which must have sufficient height to meet its advertised nominal range. As such major lights are necessarily supported by fairly substantial structures.

Most active lighthouses display a light signal consistent with major lights. They operate automatically, i.e. unmanned. Some major light are equipped with backup lights of lower intensity that are automatically energized should there be a causality to the main light. There are many different light optic options for major lights, depending on the operational range requirement of the light signal, atmospheric clarity, background lighting, and other limitations. As LED technology improves, the Coast Guard is converting many of its major lights to LED optics. Few major lights still operate with a classical Fresnel-type lens. Since nearly every lighthouse is unique, the day signal for most major lights is the light structure itself. Offshore major lights should be given a wide berth, sea room permitting. Figure 712 depicts a typical major light.

Figure 712. Typical Major Light.

Minor light structures are usually not as substantial as major light structures. In fact many minor ATON lights consist of a single wood or steel pile driven into the seabed, with a self-contained LED, and the appropriate day signal.

713. Range Lights

A range consists of two or more beacons so positioned with respect to each other that when seen aligned they mark a line of definite bearing, the **range line** commonly delineating the centerline of a navigation channel. These aids to navigation are typically affixed with duel-colored vertically striped **dayboard**s for alignment during daylight hours and if lighted, exhibit lighted signals during periods of darkness. Some ranges exhibit a light signal 24-hours a day, which may or may not be equipped with dayboards. The rear range is designed and constructed so that it is higher than the front range to enable mariners to align the ranges; the rear range light will always be above the front light for the height of eye of the vessels transiting the range line. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) refers to ranges as Leading Lines. Figure 713 illustrates the mariner's observation of range markers from three separate aspects when transiting the Range Line: 1. Left of Range Line; 2. On the Range Line; and 3. Right of Range Line.

Range lights provide horizontal vessel positioning insight to mariners transiting the Range Line by vertically displaying white, red, green or yellow lights (rear light above and behind the forward light). The color is selected that presents the most conspicuous and least confusing signal to the mariner. Most range lights display a very narrow light beam of high intensity focused down the range line, hence the brilliance of the light signal decreases significantly when observed just a few degrees either side of the range line. The specific arc of high intensity for range lights can be found in Column 8 of the applicable Light List.

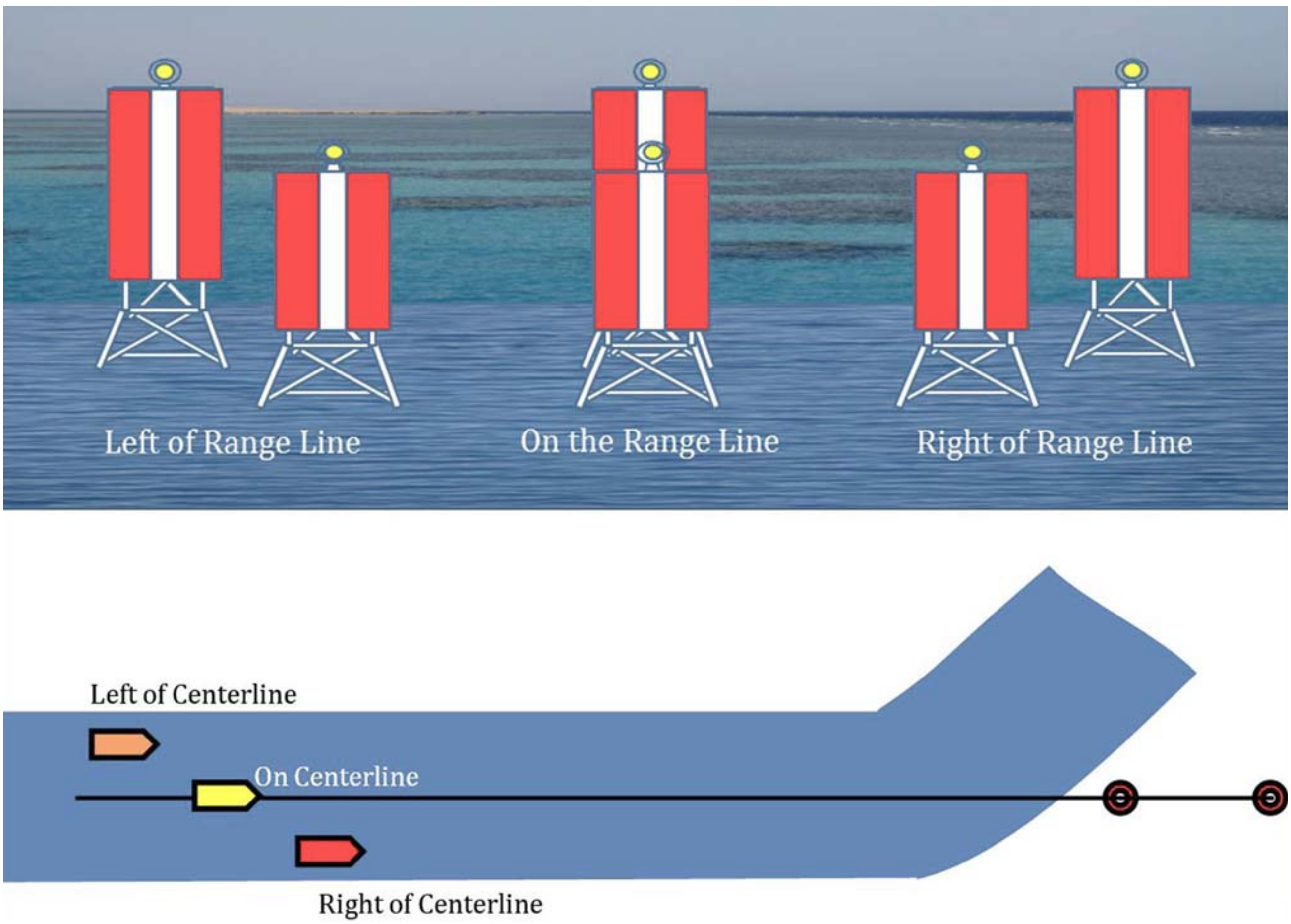


Figure 713. Example of Range Light aspects.

While range lights are conspicuous to mariners traversing the channel for which they mark, Range structures located in adjacent navigable waters can pose a hazard to navigation. Therefore, marine range structures are typically augmented with additional or passing lights to alert mariners as to the location of the range structure.

Additional lights are not readily recognizable to the mariner. They mark range structures whose light have a focal plane of 40 feet or lower. Additional lights are typically mounted above the range light optic and have the same color and light characteristic as the front range light. **Passing Lights** mark ranges whose focal plane is taller than 40 feet. They are mounted closer to the water surface, typically exhibit a white light and display light characteristics different from the rear range light. Passing lights are listed separately in the Light List and as such have a separate Light List number.

714. Directional Lights - Port Entry Lights

Directional Lights are also known as Port Entry Lights (PEL). *IALA refers to these types of lights as* ***Sector Lights****. However, the term Sector Lights in the USATONS has a distinctively different meaning* - see Section 719.

They are comprised of a single light source fitted with a very sophisticated lens that projects three or more narrow high intensity light arcs of different colors, relative to a predetermined bearing line, typically a channel centerline. Newer directional lights also include distinct light characteristics, such as flashing sectors that are readily recognizable to the observer as they move to either side away from the bearing line.

Directional lights, although usually not as sensitive as a two station range, are invaluable aids to navigation employed in those locations where establishing a two station range is impractical. They are most effective for short channel segments. Figure 714 presents an example of a three color directional light.

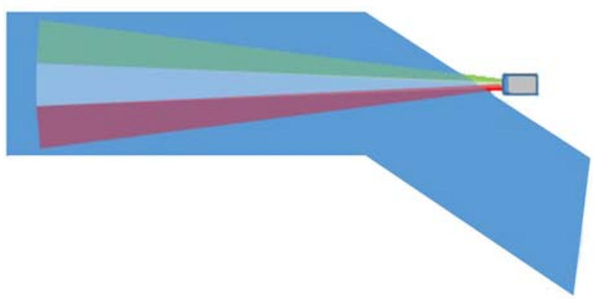


Figure 714. Example of a three color directional light.

715. Unlighted Beacons - Daybeacons

A daybeacon is identified by the color, shape, and lateral number. The simplest form of daybeacon consists of a single pile with a dayboard affixed at or near its top (see Figure 715). Daybeacons may be used to form an unlighted range.

Dayboards are affixed to all daybeacons and to most minor lights. They are shape-significant and usually have numbers and/or letters affixed to identify the specific aid to navigation. Retro-reflective background, edges, and numbers assist their identification at night when illuminated by an external light source, such as a vessel search light. Dayboard size, along with atmospheric visibility, will determine the range at which a dayboard can be detected and properly identified.

716. Aeronautical Lights

Aeronautical lights (also referred to as Aero beacons) may be the first lights observed at night when approaching the coast, they are intended primarily for aircraft navigation.

Those situated near the coast and visible from sea are listed in the *List of Lights* but are not listed in the Coast Guard Light Lists. They usually flash alternating white and green. Aeronautical lights are sequenced geographically in the *List of Lights*. However, since they are not maintained for marine navigation, they are subject to changes, as such the Coast Guard may not be informed of the changes. However, they will be published in *Notice to Airmen*.

Figure 715.Unlighted beacon.

717. Bridge Lights

Navigational lights on bridges in the U.S. are prescribed by the Coast Guard consistent with the U.S. Code and the U.S. Code of Federal Regulations (CFR). Lighting requirements vary depending on the type of bridge structure.

Fixed Bridges - Each span over a navigable waterway is required to have two green range lights with a fixed characteristic that mark the center of the navigable waterway or channel. The bridge piers are required to be lighted with fixed red lights. Per 33 CFR 118.100, some lighting schemes on fixed bridges may be consistent with the waterway's lateral ATON system.

Swing bridges when closed are required to display three fixed red lights, one at the center of the span and one on each end of the span. When the span is open, the lights are to show fixed green in line with the horizontal axis of the bridge, so as two green lights can be seen from either direction. Bridge piers display lights similar to those for fixed bridges. **Bascule bridges**, single or double span, are required to display fixed red lights at the end of the span(s) when lifted. Once the span is completely open - fixed green lights are displayed. Bridge piers display lights similar to those for fixed bridges. The lighting requirements for **lift bridges** are similar to bascule bridges. A fixed red light is displayed at the center of the span when it is down and a fixed green light is displayed when the span is completely open.

Refer to the U.S. Coast Guard Office of Bridge Administration pamphlet *Bridge Lighting and Other Signals* for graphic depictions of bridge lighting regulations.

Bridges may also be augmented with reflective material, radar reflectors, RACON signals - typically marking the center span of the navigable waterway - or AIS-ATON signals - typically marking the bridge piers and other obstructions.

AIDS TO NAVIGATION LIGHT CHARACTERISTICS

718. Characteristics

An aid to navigation light has a distinctive rhythm or characteristic, which is the sequence of light and dark periods within a specified time period; or when the light is on or off. The period of darkness within the sequence is referred to as the **eclipse**. The sequence includes the number of light and eclipse periods within a specified time duration. For example, the sequence of an aid to navigation displaying a standard Flashing 4 second light signal would be observed as 0.4 second period of light followed by a 3.6 second eclipse per each 4 second sequence.

The light signal color does not impact the light characteristic but adds to the distinguishing features of the ATON light signal. If, in the previous example, the light signal color was green, then the light's characteristic would be further refined as Flashing Green every 4 seconds.

Generally, **Flashing** light signals display light for a much shorter period than the accompanying eclipse. The period of light is greater than the eclipse with an **Occulting** light signal. **Isophase** light signals display equal periods of light and eclipse. **Group Flashing** signals display a specified number of flashes followed by a longer eclipse period. An **Alternating** light characteristic will display more than one light within the specified sequence.

The light characteristic of an aid to navigation is one of the methods for distinguishing one light signal from another and for conveying specific marine safety information. For example, a quick flashing light in a lateral system typically indicates that the axis of the waterway or channel changes direction at or near that location.

Most lighted aids to navigation are equipped with light sensors, daylight controls, that turn the light signal off during daylight. Due to a variety of factors, not all ATON lights in an area turn off or on at the same time. It is not uncommon to observe some ATON lights on while others are off, especially during twilight or during heavy overcast conditions.

The following table lists some of the more common ATON light signal rhythms/characteristics (see Table 718).

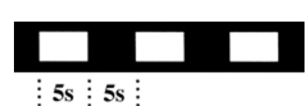
TYPE	ABBREVIATION	GENERAL DESCRIPTION	ILLUSTRATION*
Fixed	F.	A continuous and steady light.	
Occulting	Oc.	The total duration of light in a period is longer than the total duration of darkness and the intervals of darkness (eclipses) are usually of equal duration. Eclipse regularly repeated.	
Group occulting	Oc.(2)	An occulting light for which a group of eclipses, specified in number, is regularly repeated.	
Composite group occulting	Oc.(2+1)	A light similar to a group occulting light except that successive groups in a period have different numbers of eclipses.	
Isophase	Iso	A light for which all durations of light and darkness are clearly equal.	

Table 718. Light rhythm characteristics.

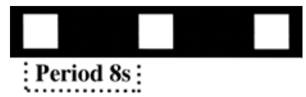
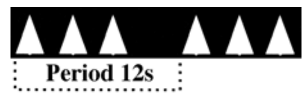
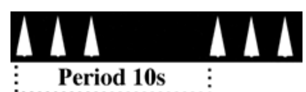
TYPE	ABBREVIATION	GENERAL DESCRIPTION	ILLUSTRATION*
Flashing	Fl.	A light for which the total duration of light in a period is shorter than the total duration of darkness and the appearances of light (flashes) are usually of equal duration (at a rate of less than 50 flashes per minute).	
Long flashing	L.Fl.	A single flashing light for which an appearance of light of not less than 2 sec. duration (long flash) is regularly repeated.	
Group flashing	Fl.(3)	A flashing light for which a group of flashes, specified in number, is regularly repeated.	
Composite group flashing	Fl.(2+1)	A light similar to a group flashing light except that successive groups in a period have different numbers of flashes.	
Quick flashing	Q.	A light for which a flash is regularly repeated at a rate of not less than 50 flashes per minute but less than 80 flashes per minute.	
Group quick flashing	Q.(3)	A light for which a specified group of flashes is regularly repeated; flashes are repeated at a rate of not less than 50 flashes per minute but less than 80 flashes per minute.	
	Q.(9)		
	Q.(6)+L.Fl.		
Interrupted quick flashing	I.Q.	A light for which the sequence of quick flashes is interrupted by regularly repeated eclipses of constant and long duration.	
Very quick flashing	V.Q.	A light for which a flash is regularly repeated at a rate of not less than 80 flashes per minute but less than 160 flashes per minute.	

Table 718. Light rhythm characteristics.

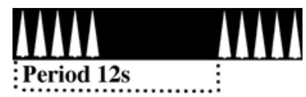
TYPE	ABBREVIATION	GENERAL DESCRIPTION	ILLUSTRATION*
Group very quick flashing	V.Q.(3)	A light for which a specified group of very quick flashes is regularly repeated.	
	V.Q.(9)		
	V.Q.(6)+L.Fl.		
Interrupted very quick flashing	I.V.Q.	A light for which the sequence of very quick flashes is interrupted by regularly repeated eclipses of constant and long duration.	
Ultra quick flashing	U.Q.	A light for which a flash is regularly repeated at a rate of not less than 160 flashes per minute.	
Interrupted ultra quick flashing	I.U.Q.	A light for which the sequence of ultra quick flashes is interrupted by regularly repeated eclipses of constant and long duration.	
Composite group flashing	Fl.(2+1)	A light similar to a group flashing light except that successive groups in a period have different numbers of flashes.	
Morse code	Mo.(U)	A light for which appearances of light of two clearly different durations are grouped to represent a character or characters in Morse Code.	
Fixed and flashing	F.Fl.	A light for which a fixed light is combined with a flashing light of greater luminous intensity.	
Alternate light	Al.	A light showing different colors alternately	* Periods shown are examples only.
NOTE: Alternating lights may be used in combined form with most of the previous types of lights			

Table 718. Light rhythm characteristics.

719. Light Sectors

A light sector is the arc over which a light is visible, described in degrees true, as observed from seaward towards the light. Sectors may be used to define the distinctive color difference of two adjoining sectors, or an obscured sector.

When different color sectors are displayed from a single light (not to be confused with Directional or Port Entry Lights) one or more of the sectors are typically red indicating danger areas that mariners should avoid. Usually the color of the light is white with the red sector(s) annotated on the chart and column 4 of the Light List entry for the light. For example, the characteristic for a typical shoal light is entered in the Light List as "FL W 5s (R Sector)."

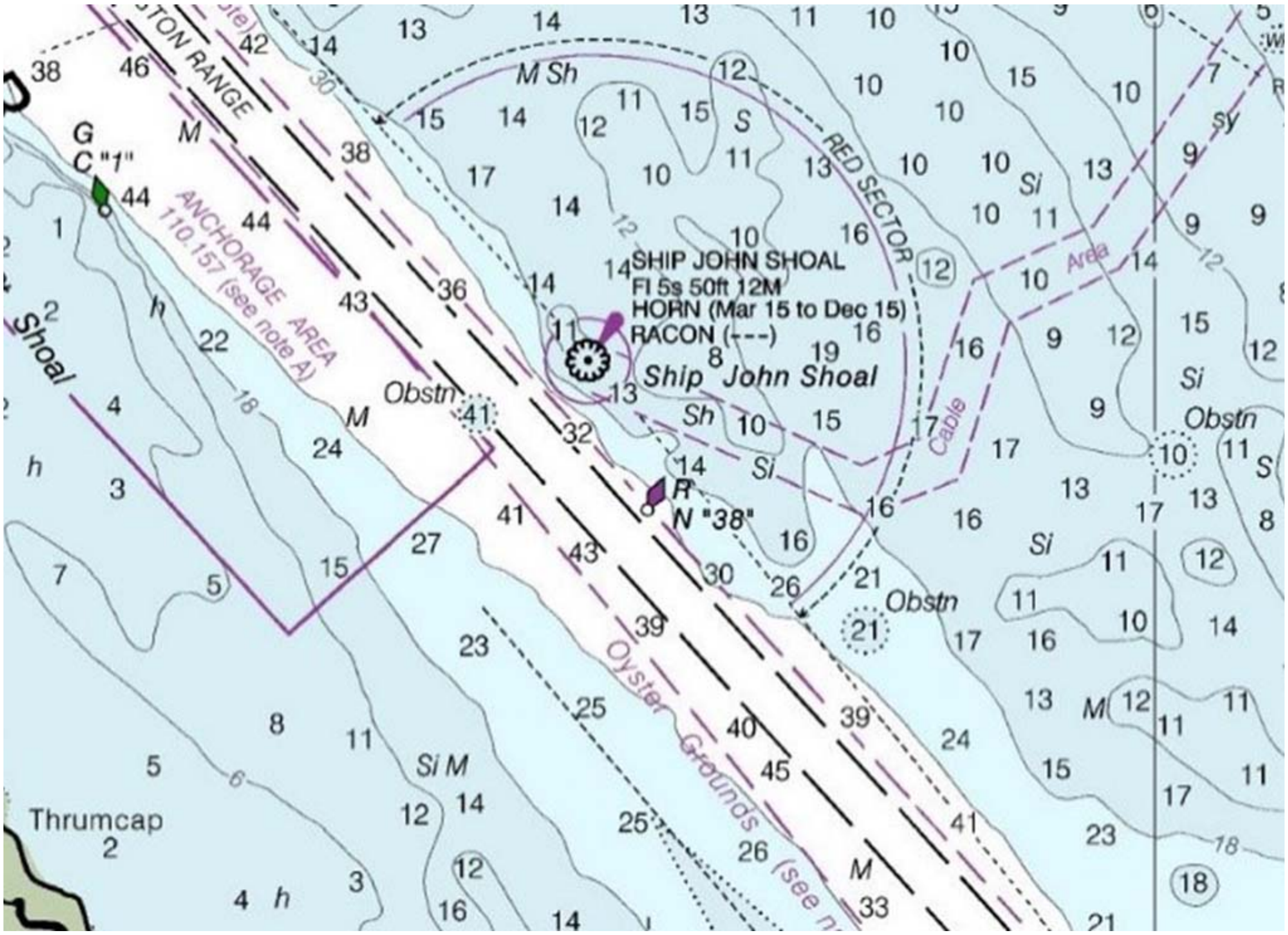


Figure 719. Portion of a chart depicting a light sector.

The transition from one color to another is not abrupt. The colors change through an arc of uncertainty of 2° or greater, depending on the optical design of the light. Therefore determining bearings by observing the color change is less accurate than obtaining a bearing with an azimuth circle. Figure 719 depicts a light sector example as found on a nautical chart.

720. Factors Affecting Range and Characteristics

Atmospheric conditions have a considerable impact on the distance at which an ATON light can be detected and recognized. Fog, smoke, haze, dust, and various forms of precipitation usually reduce detection and recognition distance. On the other hand, the atmospheric refraction of light may actually cause a navigation aid to be detected at a greater distance than ordinary circumstances would dictate. Some atmospheric conditions coupled with the geographic distance from a light may reduce the apparent duration of a light's flash, or give white lights a reddish hue. At times in clear weather green lights may appear to have a more whitish hue. Aid to navigation light signals placed at higher elevations are more frequently obscured by clouds, mist, and fog than those near sea level. In regions where ice conditions prevail, ice and snow may cover the optic of the light signal reducing its luminous range and/or altering the apparent signal color seen by the observer.

The distance from a light cannot be estimated by its apparent brightness. There are too many factors that can affect a light signal's perceived intensity. Also, a powerful, distant light may sometimes be confused with a smaller closer light with similar characteristics. Every light signal observed should be carefully evaluated to ensure that the light signal is properly identified with its proper aid to navigation.

The presence, location, and number of **shore lights** and background lighting may make it difficult to distinguish aid to navigation light signals from the background lighting. Aid to navigation lights may be obscured by various shore obstructions, be they natural or man-made. Mariners should report any such obstruction to the nearest Coast Guard unit.

A light signal's **loom** is sometimes seen through haze or the reflection from low-lying clouds when the light is beyond its geographic range. Only the most powerful lights can generate a loom. The loom may be sufficiently defined to obtain a bearing.

At short distances, some light signals inside a lighthouse copula emitted via rotating lanterns may show a faint continuous light, or faint flashes, between regular flashes. This is likely due to reflections of a rotating lens on panes of glass in the lighthouse copula.

If a light is not observed within a reasonable time after prediction the prudent mariner will, without delay, ascertain the vessel's position via other position fixing methods to determine the possibility of standing into danger. The inability to observe a light signal may be caused by the light being obscured or extinguished.

The apparent characteristic of a complex light may change with the distance of the observer. For example, a light with a characteristic of fixed white and alternating flashing white and red may initially show as a simple flashing white light. As the vessel draws nearer, the red flash will become visible and the characteristic will apparently be alternating flashing white and red. Later, the fainter fixed white light will be seen between the flashes and the true characteristic of the light finally recognized as fixed white, alternating flashing white and red (F W Al W R). This phenomenon results from the greater luminous intensity generated by the white light signal. White lights can produce the greatest luminous intensity, green lights less so, and red lights are the least of the three. This fact also accounts for the different ranges given in the Light Lists for some multi-color sector lights. A light signal with the same light source has different luminous and nominal ranges according to the color of the lens or glass.

All observed aid to navigation discrepancies should be reported immediately to the nearest Coast Guard unit.

SOUND SIGNALS

721. Types of Sound Signals

Most lighthouses and offshore light platforms, as well as some minor light structures and buoys, are equipped with sound-producing devices to help the mariner in periods of low visibility. Charts and *Light Lists* contain the information required for positive identification. Buoys fitted with bells, gongs, or whistles actuated by wave motion may produce no sound when the sea is calm. Sound signals are not designed to identify the buoy or beacon for navigation purposes. Rather, they allow the mariner to pass clear of the buoy or beacon during low visibility.

Sound signals vary. The navigator must use the *Light List* to determine the exact length of each blast and silent interval. The various types of sound signals also differ in tone, facilitating recognition of the respective stations.

Diaphones produce sound with a slotted piston moved back and forth by compressed air. Blasts may consist of a high and low tone. These alternate-pitch signals are called “two-tone.” Diaphones are not used by the Coast Guard, but the mariner may find them on some private navigation aids.

Horns produce sound by means of a disc diaphragm operated pneumatically or electrically. Duplex or triplex horn units of differing pitch produce a chime signal.

Sirens produce sound with either a disc or a cup-shaped rotor actuated electrically or pneumatically. Sirens are not used on U.S. navigation aids.

Whistles use compressed air emitted through a circumferential slot into a cylindrical bell chamber.

Bells and gongs are sounded with a mechanically operated hammer.

722. Limitations of Sound Signals

As aids to navigation, sound signals have serious limitations because sound travels through the air in an unpredictable manner.

It has been clearly established that:

1. Sound signals are heard at greatly varying distances and that the distance at which a sound signal can be heard may vary with the bearing and timing of the signal.
2. Under certain atmospheric conditions, when a sound signal has a combination high and low tone, it is not unusual for one of the tones to be inaudible. In the case of sirens, which produce a varying tone, portions of the signal may not be heard.
3. When the sound is screened by an obstruction, there are areas where it is inaudible.
4. Operators may not activate a remotely controlled sound aid for a condition unobserved from the controlling station.
5. Some sound signals cannot be immediately started.
6. The status of the vessel’s engines and the location of the observer both affect the effective range of the aid.

These considerations justify the utmost caution when navigating near land in a fog. Navigator can never rely on sound signals alone; they should continuously monitor both the radar and fathometer when in low visibility. They should place lookouts in positions where the noises in the ship are least likely to interfere with hearing a sound signal. The aid upon which a sound signal rests is usually a good radar target, but collision with the aid or the danger it marks is always a possibility.

Emergency signals are sounded at some of the light and fog signal stations when the main and stand-by sound signals are inoperative. Some of these emergency sound signals are of a different type and characteristic than the main sound signal. The characteristics of the emergency sound signals are listed in the *Light List*.

Mariners should never assume:

1. That they are out of ordinary hearing distance because s/he fails to hear the sound signal.
2. That because they hear a sound signal faintly, they are far from it.
3. That because they hear it clearly, they are near it.
4. That the distance from and the intensity of a sound on any one occasion is a guide for any future occasion.
5. That the sound signal is not sounding because they do not hear it, even when in close proximity.
6. That the sound signal is emanating from the apparent direction the sound heard.

MARITIME BUOYAGE SYSTEMS

723. Buoyage System Types

There are two major types of buoyage systems in the maritime world today, the **lateral system** and the **cardinal system**.

The lateral system is best suited for well-defined channels. The description of each buoy indicates the direction of danger relative to the course which is normally followed. In principle, the positions of marks in the lateral system are determined by the **general direction** taken by the mariner when approaching port from seaward. These positions may also be determined with reference to the main stream of flood current. The United States Aids to Navigation System is a lateral system.

The cardinal system is best suited for coasts with numerous isolated rocks, shoals, and islands, and for dangers in the open sea. The characteristic of each buoy indicates the approximate true bearing of the danger it marks. Thus, an eastern quadrant buoy marks a danger which lies to the west of the buoy. The following pages diagram the cardinal and lateral buoyage systems as found outside the United States.

724. The IALA Maritime Buoyage System

There has long been disagreement over the way in which buoy lights should be used since they first appeared towards the end of the 19th century. In particular, some countries favored using red lights to mark the port side of channels when entering from sea while others favored them for marking the starboard side. Another major difference of opinion revolved around the principles to be applied when designing buoy systems. Most countries adopted the principle of the **Lateral** system while several other countries also favored using the principle of the **Cardinal system**.

In 1957 the, **International Association of Lighthouse Authorities (IALA)** was formed in order to support the goals of the technical lighthouse conferences which had been convening since 1929. Attempts to bring complete unity had little success. Fresh impetus was given to the task of the IALA Committee, by a series of disastrous wrecks in the Dover Strait area in 1971. These wrecks, situated in one lane of a traffic separation scheme, defied all attempts to mark them in a way that could be readily understood by mariners.

To meet the conflicting requirements, it was deemed necessary to formulate two Lateral systems, one using the color red to mark the port side of the channels entering from sea and the other using the color red to mark the starboard side of channels. These were called System A and System B respectively. The rules for System A, which included both cardinal and lateral marks, were completed in 1976 and agreed by the International Maritime Organization (IMO). The System was introduced in 1977 and its use has gradually spread throughout Europe, Australia, New Zealand, Africa, the Gulf and some Asian Countries.

The rules for System B were completed in early 1980. These were considered suitable for application in North, Central and South America. Japan, Republic of Korea and Philippines.

The rules for the two Systems were so similar that the IALA Executive Committee was able to combine the two sets of rules into one, known as "The **IALA Maritime Buoyage System**". This single set of rules allows Aids to Navigation Authorities the choice of using red to port or red to starboard, on a regional basis; the two regions being known as **Region A** and **Region B**.

At a Conference convened by IALA in November 1980 with the assistance of IMO and the International Hydrographic Organization (IHO) Aid to Navigation Authorities from 50 countries and the representatives of nine International Organizations concerned with aids to navigation met and agreed to adopt the rules of the new combined system. The boundaries of the buoyage regions were also decided and illustrated on a map annexed to the rules.

Today IALA operates as a non-governmental non-profit international organization, devoted to the harmonization of marine aids to navigation. It promotes information exchange and recommends improvements based on new technologies

725. Types of Marks

The **IALA Maritime Buoyage System** applies to all fixed and floating marks, other than lighthouses, sector lights, range lights, daymarks, lightships and large navigational buoys, which indicate:

1. The side and center-lines of navigable channels
2. Natural dangers, wrecks, and other obstructions
3. Regulated navigation areas
4. Other important features

Most lighted and unlighted beacons other than range marks are included in the system. In general, beacon topmarks will have the same shape and colors as those used on buoys. The system provides five types of marks which may be used in any combination:

1. Lateral marks indicate port and starboard sides of channels.
2. Cardinal marks, named according to the four points of the compass, indicate that the navigable water lies to the named side of the mark.
3. Isolated danger marks erected on, or moored directly on or over, dangers of limited extent.
4. Safe water marks, such as midchannel buoys.
5. Special marks, the purpose of which is apparent from reference to the chart or other nautical documents.

Characteristics of Marks

The significance of a mark depends on one or more features:

1. By day—color, shape, and topmark
2. By night—light color and phase characteristics

Colors of Marks

The colors red and green are reserved for lateral marks, and yellow for special marks. The other types of marks have black and yellow or black and red horizontal bands, or red and white vertical stripes.

Shapes of Marks

There are five basic buoy shapes:

1. Can
2. Cone
3. Sphere
4. Pillar
5. Spar

In the case of can, conical, and spherical, the shapes have lateral significance because the shape indicates the correct side to pass. With pillar and spar buoys, the shape has no special significance.

The term “pillar” is used to describe any buoy which is smaller than a large navigation buoy (LNB) and which has a tall, central structure on a broad base; it includes beacon buoys, high focal plane buoys, and others (except spar buoys) whose body shape does not indicate the correct side to pass.

Topmarks

The IALA System makes use of **can, conical, spherical,** and **X-shaped** topmarks only. Topmarks on pillar and spar buoys are particularly important and will be used wherever practicable, but ice or other severe conditions may occasionally prevent their use.

Colors of Lights

Where marks are lighted, red and green lights are reserved for lateral marks, and yellow for special marks. The other types of marks have a white light, distinguished one from another by phase characteristic.

Phase Characteristics of Lights

Red and green lights may have any phase characteristic, as the color alone is sufficient to show on which side they should be passed. Special marks, when lighted, have a yellow light with any phase characteristic not reserved for white lights of the system. The other types of marks have clearly specified phase characteristics of white light: various quick-flashing phase characteristics for cardinal marks, group flashing (2) for isolated danger marks, and relatively long periods of light for safe water marks.

Some shore lights specifically excluded from the IALA System may coincidentally have characteristics corresponding to those approved for use with the new marks. Care is needed to ensure that such lights are not misinterpreted.

726. IALA Lateral Marks

Lateral marks are generally used for well-defined channels; they indicate the port and starboard hand sides of the route to be followed, and are used in conjunction with a **conventional direction of buoyage**.

This direction is defined in one of two ways:

1. **Local direction of buoyage** is the direction taken by the mariner when approaching a harbor, river estuary, or other waterway from seaward.
2. **General direction of buoyage** is determined by the buoyage authorities, following a clockwise direction around continental land-masses, given in sailing directions, and, if necessary, indicated on charts by a large open arrow symbol.

In some places, particularly straits open at both ends, the local direction of buoyage may be overridden by the general direction.

Along the coasts of the United States, the characteristics assume that proceeding "from seaward" constitutes a clockwise direction: a southerly direction along the Atlantic coast, a westerly direction along the Gulf of Mexico coast, and a northerly direction along the Pacific coast. On the Great Lakes, a westerly and northerly direction is taken as being "from seaward" (except on Lake Michigan, where a southerly direction is used). On the Mississippi and Ohio Rivers and their tributaries, the characteristics of aids to navigation are determined as proceeding from sea toward the head of navigation. On the Intracoastal Waterway, proceeding in a generally southerly direction along the Atlantic coast, and in a generally westerly direction along the gulf coast, is considered as proceeding "from seaward."

727. IALA Cardinal Marks

A **cardinal mark** is used in conjunction with the compass to indicate where the mariner may find the best navigable water. It is placed in one of the four quadrants (north, east, south, and west), bounded by the true bearings NW-NE, NE-SE, SE-SW, and SW-NW, taken from the point of interest. A cardinal mark takes its name from the quadrant *in which it is placed*.

The mariner is safe if they pass north of a north mark, east of an east mark, south of a south mark, and west of a west mark.

A cardinal mark may be used to:

1. Indicate that the deepest water in an area is on the named side of the mark.
2. Indicate the safe side on which to pass a danger.
3. Emphasize a feature in a channel, such as a bend, junction, bifurcation, or end of a shoal.

Cardinal System Topmarks

Black double-cone topmarks are the most important feature, by day, of cardinal marks. The cones are vertically placed, one over the other. The arrangement of the cones is very logical: North is two cones with their points up (as in "north-up"). South is two cones, points down. East is two cones with bases together, and west is two cones with points together, which gives a wineglass shape. "West is a Wineglass" is a memory aid.

Cardinal marks displays topmarks whenever practicable, with the cones as large as possible and clearly separated.

Colors

Black and yellow horizontal bands are used to color a cardinal mark. The position of the black band, or bands, is related to the points of the black topmarks.

N	Points up	Black above yellow
S	Points down	Black below yellow
W	Points together	Black, yellow above and below
E	Points apart	Yellow, black above and below

Shape

The shape of a cardinal mark is not significant, but buoys must be pillars or spars.

Lights

When lighted, a cardinal mark exhibits a white light; its characteristics are based on a group of quick or very quick flashes which distinguish it as a cardinal mark and indicate its quadrant. The distinguishing quick or very quick flashes are:

North—Uninterrupted
East—three flashes in a group
South—six flashes in a group followed by a long flash
West—nine flashes in a group

As a memory aid, the number of flashes in each group can be associated with a clock face: 3 o'clock—E, 6 o'clock—S, and 9 o'clock—W.

The long flash (of not less than 2 seconds duration), immediately following the group of flashes of a south cardinal mark, is to ensure that its six flashes cannot be mistaken for three or nine.

The periods of the east, south, and west lights are, respectively, 10, 15, and 15 seconds if quick flashing; and 5, 10, and 10 seconds if very quick flashing.

Quick flashing lights flash at a rate between 50 and 79 flashes per minute, usually either 50 or 60. Very quick flashing lights flash at a rate between 80 and 159 flashes per minute, usually either 100 or 120.

It is necessary to have a choice of quick flashing or very quick flashing lights in order to avoid confusion if, for example, two north buoys are placed near enough to each other for one to be mistaken for the other.

728. IALA Isolated Danger Marks

An **isolated danger mark** is erected on, or moored on or above, an isolated danger of limited extent which has navigable water all around it. The extent of the surrounding navigable water is immaterial; such a mark can, for example, indicate either a shoal which is well offshore or an islet separated by a narrow channel from the coast.

Position

On a chart, the position of a danger is the center of the symbol or sounding indicating that danger; an isolated danger buoy may therefore be slightly displaced from its geographic position to avoid overprinting the two symbols. The smaller the scale, the greater this offset will be. At very large scales the symbol may be correctly charted.

Topmark

A black double-sphere topmark is, by day, the most important feature of an isolated danger mark. Whenever practicable, this topmark will be carried with the spheres as large as possible, positioned vertically, and clearly separated.

Color

Black with one or more red horizontal bands are the colors used for isolated danger marks.

Shape

The shape of an isolated danger mark is not significant, but a buoy will be a pillar or a spar.

Light

When lighted, a white flashing light showing a group of two flashes is used to denote an isolated danger mark. As a memory aid, associate two flashes with two balls in the topmark.

729. IALA Safe Water Marks

A **safe water mark** is used to indicate that there is navigable water all around the mark. Such a mark may be used as a center line, mid-channel, or landfall buoy.

Color

Red and white vertical stripes are used for safe water marks, and distinguish them from the black-banded, danger-marking marks.

Shape

Spherical, pillar, or spar buoys may be used as safe water marks.

Topmark

A single red spherical topmark will be carried, whenever practicable, by a pillar or spar buoy used as a safe water mark.

Lights

When lighted, safe water marks exhibit a white light. This light can be occulting, isophase, a single long flash, or Morse "A." If a long flash (i.e. a flash of not less than 2 seconds) is used, the period of the light will be 10 seconds. As a memory aid, remember a single flash and a single sphere topmark.

730. IALA Special Marks

A **special mark** may be used to indicate a special area or feature which is apparent by referring to a chart, sailing directions, or notices to mariners. Uses include:

1. Ocean Data Acquisition System (ODAS) buoys
2. Traffic separation marks
3. Spoil ground marks
4. Military exercise zone marks
5. Cable or pipeline marks, including outfall pipes
6. Recreation zone marks

Another function of a special mark is to define a channel within a channel. For example, a channel for deep draft vessels in a wide estuary, where the limits of the channel for normal navigation are marked by red and green lateral buoys, may have its boundaries or centerline marked by yellow buoys of the appropriate lateral shapes.

Color

Yellow is the color used for special marks.

Shape

The shape of a special mark is optional, but must not conflict with that used for a lateral or a safe water mark. For example, an outfall buoy on the port hand side of a channel could be can-shaped but not conical.

Topmark

When a topmark is carried it takes the form of a single yellow X.

Lights

When a light is exhibited it is yellow. It may show any phase characteristic except those used for the white lights of cardinal, isolated danger, and safe water marks. In the case of ODAS buoys, the phase characteristic used is group-flashing with a group of five flashes every 20 seconds.

731. IALA New Dangers

A newly discovered hazard to navigation not yet shown on charts, included in sailing directions, or announced by a *Notice to Mariners* is termed a **new danger**. The term covers naturally occurring and man-made obstructions.

Marking

A new danger is marked by one or more cardinal or lateral marks in accordance with the IALA system rules. If the danger is especially grave, at least one of the marks will be duplicated as soon as practicable by an identical mark until the danger has been sufficiently identified.

Lights

If a lighted mark is used for a new danger, it must exhibit a quick flashing or very quick flashing light. If a cardinal mark is used, it must exhibit a white light; if a lateral mark, a red or green light.

Racons

The duplicate mark may carry a Racon, Morse coded D, showing a signal length of 1 nautical mile on a radar display.

732. Chart Symbols and Abbreviations

Spar buoys and spindle buoys are represented by the same symbol; it is slanted to distinguish them from upright beacon symbols. The abbreviated description of the color of a buoy is given under the symbol. Where a buoy is colored in bands, the colors are indicated in sequence from the top. If the sequence of the bands is not known, or if the buoy is striped, the colors are indicated with the darker color first.

Topmarks

Topmark symbols are solid black (except when the topmark is red).

Lights

The period of the light of a cardinal mark is determined by its quadrant and its flash characteristic (either quick-flashing or a very quick-flashing). The light's period is less important than its phase characteristic. Where space on charts is limited, the period may be omitted.

Light Flares

Magenta light-flares are normally slanted and inserted with their points adjacent to the position circles at the base of the symbols so the flare symbols do not obscure the topmark symbols.

Automatic Identification System (AIS)

Magenta circle with AIS text to the Navigation Aid depicts the existence of an AIS station. These aids broadcast their presence, identity, position and status at least every three minutes or as needed. These broadcasts can originate from a station located on an existing physical aid to navigation (Real AIS ATON) or from another location (Synthetic AIS ATON). A Virtual AIS is electronically charted, but non-existent as a physical aid to navigation (Virtual AIS ATON).

Radar Reflectors

According to IALA rules, radar reflectors are not necessarily charted for several reasons. First, all major buoys are fitted with radar reflectors. It is also necessary to reduce the size and complexity of buoy symbols and associated legends. Finally, it is understood that, in the case of cardinal buoys, buoyage authorities place the reflector so that it cannot be mistaken for a topmark.

The symbols and abbreviations of the IALA Maritime Buoyage System may be found in *U.S. Chart No. 1* and in foreign equivalents.

UNITED STATES AIDS TO NAVIGATION SYSTEM (USATONS)

733. General U.S. Aids to Navigation System

The United States has adopted the major features of the IALA system, consistent with Region B for the United States Aids to Navigation System (USATONS).

The primary objective of the USATONS is to mitigate transit risks to promote the safe, economic, and efficient movement of military, commercial, and other vessels by assisting navigators in determining their position, a safe course, and warning them of dangers and obstructions.

Colors

Under this system, green buoys and beacons with green square dayboards mark a channel or waterway's port (left) side when entering port from sea and obstructions which must be passed by keeping the aid to navigation to port. Red buoys and beacons with red triangle dayboards mark a channel or waterway's starboard (right) side when entering port from sea and obstructions which must be passed by keeping the aid to navigation to starboard. Hence the phrase *Red Right Returning*.

Red and green horizontally banded **preferred channel** buoys and beacons (see Figure 733a) with red and green horizontally banded dayboards mark junctions or bifurcations in a channel or obstructions which may be passed on either side. If the topmost band is green, then the preferred channel will be followed by keeping the aid to navigation to port when entering port from sea. If the topmost band is red, then the preferred channel will be followed by keeping the

Figure 733a. Preferred channel or "junction" buoy.

Red and white vertically striped **safe water** buoys and beacons (see Figure 733b) with red and white vertically striped dayboards mark a fairway or mid-channel.

Reflective material is placed on buoys and beacon dayboards to assist in their detection at night with a searchlight. The color of the reflective material agrees with the aid to navigation color. Red or green reflective material may be placed on preferred channel (junction) ATON; red if topmost band is red, or green if the topmost band is green. White reflective

Figure 733b. Safe water buoy.

material is used on safe water ATON. Special purpose buoys and beacons display yellow reflective material. Warning or regulatory buoys and beacons display orange reflective horizontal bands and a warning symbol.

Shapes

Certain unlighted buoys are differentiated by shape. Red buoys and red and green horizontally banded buoys with the topmost band red are cone-shaped buoys called **nuns**. Green buoys and green and red horizontally banded buoys with the topmost band green are cylinder-shaped buoys called **cans**.

Unlighted red and white vertically striped buoys may be pillar shaped or spherical. Lighted buoys, sound buoys, and spar buoys are not differentiated by shape to indicate the side on which they should be passed. Their purpose is indicated not by shape but by the color, number, or light characteristics.

Beacon dayboards also have shape significance. Red boards are triangle-shaped and green boards are square. Safe water beacons are marked with octagonal-shaped red and white vertically colored boards. A range is marked with rectangular-shaped board vertically striped (one color running down the center flanked by another color - a red board with a with center stripe for example).

There are also diamond-shaped special purpose and square-shaped information and regulatory boards.

Numbers

All solid colored buoys and beacons are numbered, red ATON exhibiting even numbers and green ATON odd numbers. The number values increase from seaward upstream or toward land. Other multiple colored ATON are not numbered but they may exhibit a letter for identification. In fact any ATON may be assigned a letter for identification.

Light Colors

Red lights are used only on red or red and green horizontally banded buoys and beacons with red triangle-shaped dayboards or horizontally banded triangle-shaped dayboards with red being the topmost band.

Green lights are used only on the green buoys or green and red horizontally banded buoys with the topmost band green and beacons with green square-shaped dayboards or green and red horizontally banded square-shaped dayboards with the green as the topmost band.

White lights are used on **safe water** buoys and beacons showing a Morse Code “A” characteristic and on Information and Regulatory buoys and beacons

Light Characteristics

Lights on red buoys or green buoys, if not occulting or isophase, will generally be regularly flashing (Fl). For ordinary purposes, the frequency of flashes will be not more than 50 flashes per minute. Lights with a distinct cautionary significance, such as at sharp turns or marking dangerous obstructions, will flash not less than 50 flashes but not more than 80 flashes per minute (quick flashing, Q). Lights on preferred channel buoys will show a series of group flashes with successive groups in a period having a different number of flashes - composite group flashing (or a quick light in which the sequence of flashes is interrupted by regularly repeated eclipses of constant and long duration). Lights on safe water buoys will always show a white Morse Code “A” (Short-Long) flash recurring at the rate of approximately eight times per minute.

Special Purpose Buoys

Buoys for special purposes are colored yellow. White buoys with orange bands are for informational or regulatory purposes. The shape of special purpose buoys has no significance.

They are not numbered, but they may be lettered. If lighted, special purpose buoys display a yellow light usually with fixed or slow flash characteristics. Information and regulatory buoys, if lighted, display white lights.

734. Intracoastal Waterway Aids to Navigation

The Intracoastal Waterway (ICW) consists of three noncontiguous segments: The Atlantic Coast Intracoastal Waterway - from Manasquan Inlet, New Jersey to Florida Bay, Florida; Florida Gulf Intracoastal Waterway - from Fort

Myers to Tarpon Springs, Florida; and Gulf Intracoastal Waterway - from Carrabelle, Florida to Port Brownsville, Texas near the U.S. border with Mexico. The ICW includes about 3,000 miles of navigable waterways using sounds, bays, rivers, sloughs, estuaries, and other natural waterway features connected as necessary with dredged channels and canals.

There is a fourth ICW segment that runs across Florida for about 150 miles from St. Lucie Inlet to Fort Myers, Florida, but it is quite shallow and not recommended for most commercial traffic.

Aids to Navigation marking the ICW are numbered clockwise along the Atlantic and Gulf Coast and display distinctive yellow retro-reflective bands, squares, and triangles.

Red buoys and beacons with red triangle-shaped dayboards, with a yellow triangle affixed and even numbers mark the starboard (right) side of the ICW channel when traveling in a general clockwise direction along the coast. Green buoys and beacons with green square-shaped daybeacons, with a yellow square affixed, and odd numbers mark the port (left) side of the ICW channel. Non-lateral aids to navigation, such as safe water marks, isolated danger marks, and front range boards are marked with a horizontal yellow band. Rear range boards do not display the yellow band. Where the ICW intersects with another U.S. Federal-maintained channel, the ICW yellow triangle or square affixed to the buoy or dayboard will indicate the ICW channel. Junctions between the ICW and privately maintained waterways are not marked with preferred channel buoys or beacons.

735. U.S. Western Rivers

The term Western Rivers includes the Mississippi River System, i.e. the Mississippi River from Lower Mississippi River Mile 155 to Upper Mississippi River Mile 857. In addition, the Western River System includes either in whole or portions of the Alabama, Arkansas, Black Warrior, Green, Missouri, Monongahela, Ohio, and Tennessee Rivers, the Tennessee-Tombigbee Waterway, and various other associated rivers and waterways.

The aids to navigation system marking the Western Rivers System conforms with Region B of the IALA Maritime Buoyage System with the following variations:

1. Buoys are not numbered and shore structures are not numbered laterally Buoys are not numbered.
2. Numbers on shore structures indicate mileage from a designated point (normally the river mouth).
3. Diamond-shaped non-lateral daymarks, red/white or green/white as appropriate, are used instead of triangular or square lateral daymarks where the river channel crosses from one bank to the other.
4. The conventional direction of buoyage, for the purpose of installing the proper aid signals, is upstream. Local terminology, however, refers to the “left” and “right” banks viewed from a vessel proceeding downstream.
5. Lights on the right descending bank show single flashing rhythms and may be green or white. Lights on the left descending bank show “group-flashing-two” rhythms and may be red or white.
6. In pooled waters (behind dams), buoys set to mark the nine-foot contour for normal pool elevations.
7. In unstable waters (free-flowing rivers), buoys are set to mark the project depth (12-foot contour) for the prevailing river stage.
8. Isolated danger marks are not used.

736. State Waterways Aids to Navigation System

In accordance with Title 33 of the Code of Federal Regulations, Subpart 66.05 - State Aids to Navigation:

“With the exception on the provisions of subpart 66.10, which are valid until December 31, 2003, aids to navigation must be in accordance with the United States Aids to Navigation System in part 62 of this subchapter.”

Therefore, the Uniform State Waterway Marking System (USWMS) is no longer a recognized aid to navigation system within any U.S. waterway, federal or state. Specifications for the superannuated USWMS can still be view in 33 CFR 66.10-15.

737. Private Aids to Navigation

Private Aids to Navigation (PATON) are those aids to navigation established, operated, and maintained by entities other than the Coast Guard, U.S. Armed Forces, or State authorities. There are three classes of PATON:

1. Class I: Aids to navigation on marine structures or other works which the owners are legally obligated to establish, maintain and operate as prescribed by the Coast Guard.
2. Class II: Aids to navigation exclusive of Class I located in waters used by general navigation.
3. Class III: Aids to navigation exclusive of Class I located in waters not ordinarily used by general navigation. Buoys are not numbered and shore structures are not numbered laterally Buoys are not numbered.

Per 33 CFR 66.01-1, “*No person, public body, or instrumentality not under the control of the Commandant, exclusive of the Armed Forces, will establish and maintain, discontinue, change or transfer ownership of any aid to maritime navigation, without first obtaining permission to do so from the Commandant”,* i.e. the Coast Guard.

In addition to Coast Guard approval, per 33 CFR 66.01-30, “Before any private aid to navigation consisting of a fixed structure [beacon] is placed in the navigable waters of the United States, authorization to erect such structure shall first be obtained from the District Engineer,

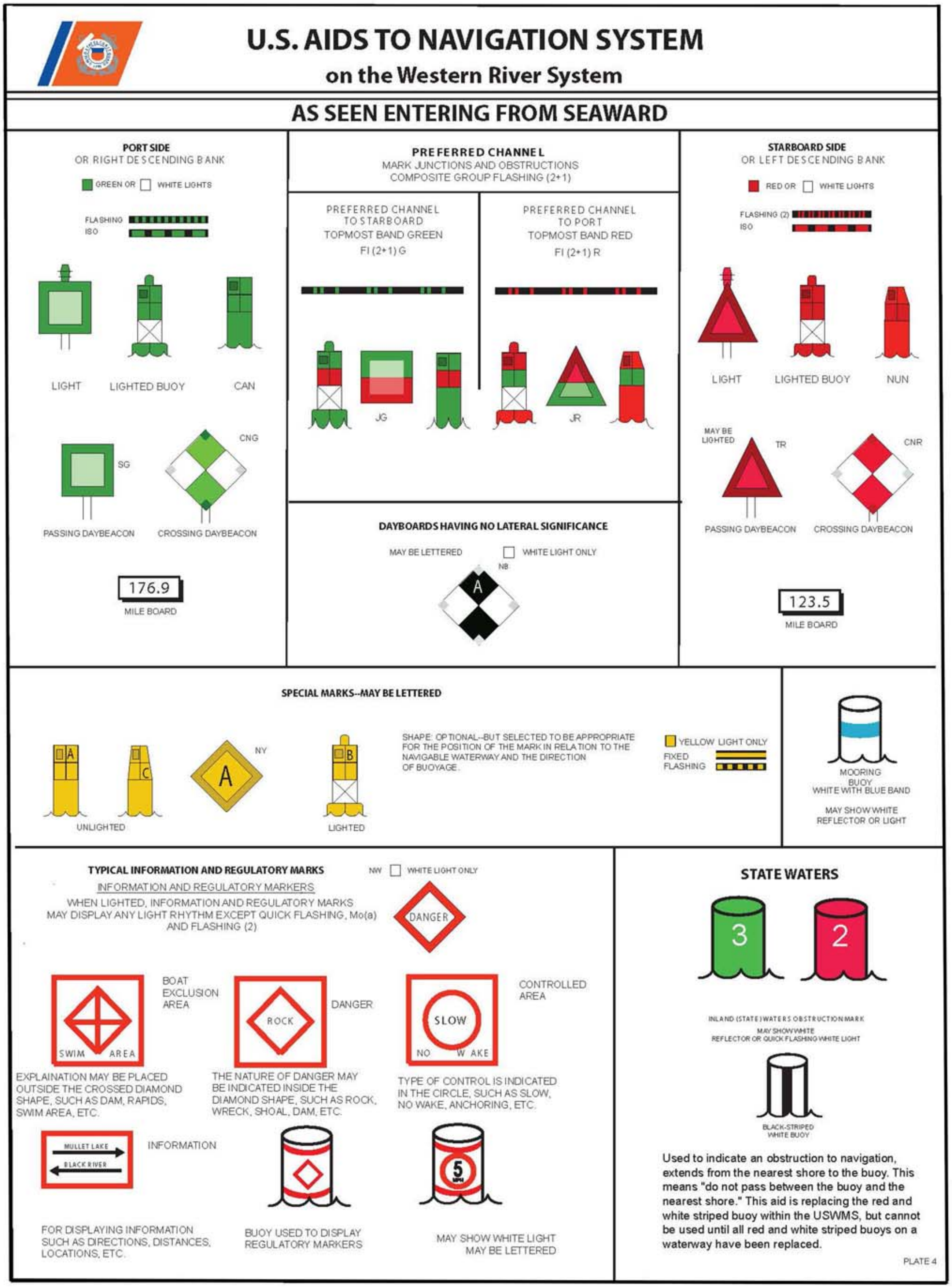


Figure 737a. U.S. Aids to Navigation - Plate 4.

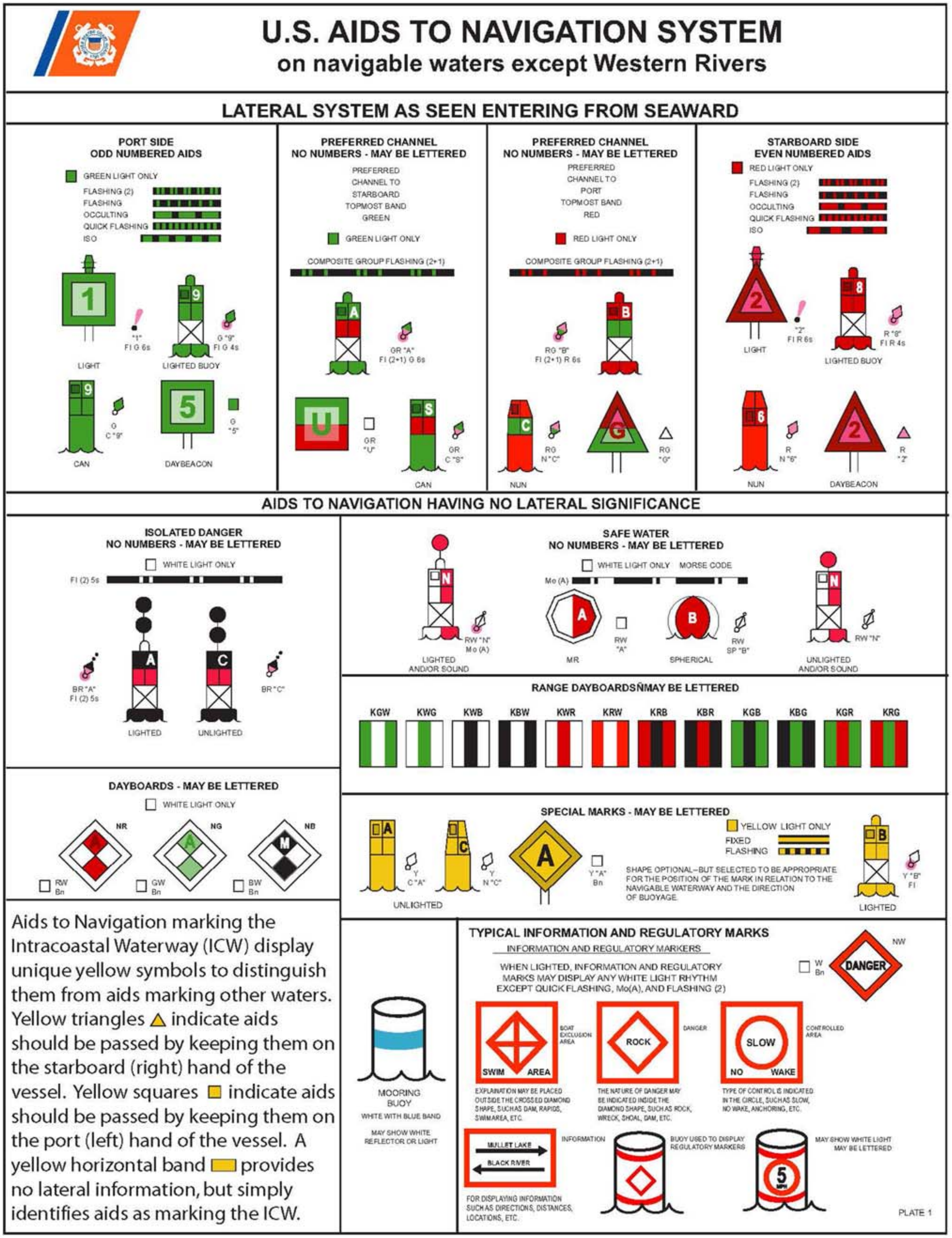


Figure 737b. U.S. Aids to Navigation - Plate 1.

U.S. Army Corps of Engineers in whose district the aid will be located."

The characteristics of a private aid to navigation must conform to those prescribed by the United States Aids to Navigation System.

Private ATON owners are responsible for maintaining their PATON, which are subject to inspection by the Coast Guard at any time without prior notice

In addition to private aids to navigation, numerous types of construction and anchor buoys are used in various oil drilling operations and marine construction. These buoys are not charted, as they are temporary, and may not be lighted well or at all. Mariners should give a wide berth to drilling and construction sites to avoid the possibility of fouling moorings. This is a particular danger in offshore oil fields, where large anchors are often used to stabilize the positions of drill rigs in deep water. Up to eight anchors may be placed at various positions as much as a mile from the drill ship. These positions may or may not be marked by buoys. Such operations in the U.S. are announced in the *Local Notice to Mariners*.

738. Interference with or Damage to Aids to Navigation

Per 33 CFR 70, "*No person, excluding the Armed Forces, shall obstruct or interfere with any aid to navigation established and maintained by the Coast Guard, or any private aid to navigation…*"

Subpart §70.01-5 states: "*Any person violating the provisions of this section shall be deemed guilty of a misdemeanor and be subject to a fine not exceeding the sum of $500 for each offense, and each day during which such violation shall continue shall be considered a new offense*."

If any vessel collides with an aid to navigation, the person in charge of the vessel is required by law to report the accident to the Officer in Charge of the nearest Coast Guard Marine Inspection unit.

739. U. S. ATONS Graphics

See Figure 737b and Figure 737a for plates to the U.S. Aids to Navigation System (on navigable waters, including the Western River System).

CHAPTER 8

COMPASSES

INTRODUCTION

800. Changes in Compass Technologies

This chapter discusses the major types of compasses available to the navigator, their operating principles, their capabilities, and limitations of their use. As with other aspects of navigation, technology is rapidly revolutionizing the field of compasses.

For much of maritime history the sole heading reference for navigators has been the magnetic compass. However, a great deal of effort and expense has gone into understanding the magnetic compass scientifically to make it as accurate as possible through research and development of elaborate compensation techniques.

Over time, technological advances like the development of more sophisticated means for obtaining accurate compass readings, such as the electro-mechanical gyrocompass, diminished traditional reliance upon the magnetic compass, relegating it to backup status in many large vessels. Later came the development of inertial navigation systems based on gyroscopic principles, but perturbations like the interruption of electrical power to the gyrocompass or inertial navigator, mechanical failure, and equipment deterioration have reminded navigators of the important reliability of the magnetic compass.

New technologies are both refining and replacing the magnetic compass as the primary heading reference and navigational tool. Although using a magnetic compass for backup is certainly advisable, today's navigator can safely rely on modern equipment, avoiding much of the effort and expense associated with the binnacle-mounted magnetic compass, such as the need for compensation, adjustment, and maintenance.

Similarly, even relatively new advances like the electro-mechanical gyrocompasses are being supplanted by far lighter, cheaper, and more dependable ring laser gyrocompasses. These devices do not operate on the principle of the gyroscope (which is based on Newton's laws of motion), but instead rely on the principles of electromagnetic energy and wave theory.

Magnetic flux gate compasses, while relying on the Earth's magnetic field for reference, have no moving parts and can compensate themselves, adjusting for both deviation and variation to provide true heading, thus completely eliminating the process of compass correction.

To the extent that one depends on the magnetic compass for navigation, it should be checked regularly and adjusted when observed errors exceed certain minimal limits, usually a few degrees for most vessels. Compensation of a magnetic compass aboard vessels where navigators are expected to rely on it offshore or during long voyages is best left to professionals. However, this chapter will present enough material for the competent navigator to do an adequate job.

Whatever type of compass being used for navigation, it is advisable to check it periodically against an error free reference to determine its error. This may be done when steering along any range during harbor and approach navigation, or by aligning any two charted objects to find the difference between their observed and charted bearings. When navigating offshore, the use of azimuths and amplitudes of celestial bodies is also an effective method; a subject covered in Chapter will also suffice, a subject covered in Chapter 15 - Azimuths and Amplitudes.

MAGNETIC COMPASSES

801. The Magnetic Compass and Magnetism

The principle of the present day magnetic compass is no different from that of the compasses used by ancient mariners. The magnetic compass consists of a magnetized needle, or an array of needles, allowed to rotate freely in the horizontal plane. The superiority of present-day magnetic compasses over ancient ones results from a better knowledge of the laws of magnetism and how it governs the behavior of the compass and from greater precision in design and construction.

Any magnetized piece of metal will have regions of concentrated magnetism called **poles**. Any such magnet will have at least two poles of opposite polarity. Magnetic force (flux) lines connect one pole of such a magnet with the other pole. The number of such lines per unit area represents the intensity of the **magnetic field** in that area.

When two magnets are placed close to each other, the like poles will repel each other and the unlike poles will attract each other.

Magnetism can be either **permanent** or **induced**. A bar having permanent magnetism will retain its magnetism when it is removed from a magnetizing field. A bar having induced magnetism will lose its magnetism when removed from the magnetizing field. Whether or not a bar will retain its magnetism on removal from the magnetizing field will depend on the strength of that field, the degree of hardness of the iron (retentivity), and upon the amount of physical stress applied to the bar while in the magnetizing field. The harder the iron, the more permanent will be the magnetism acquired.

802. Terrestrial Magnetism

Consider the Earth as a huge magnet surrounded by lines of magnetic flux connecting its two **magnetic poles**. These magnetic poles are near, but not coincidental with, the Earth's geographic poles. Since the north seeking end of a compass needle is conventionally called the **north pole**, or **positive pole**, it must therefore be attracted to a **south pole**, or **negative pole**.

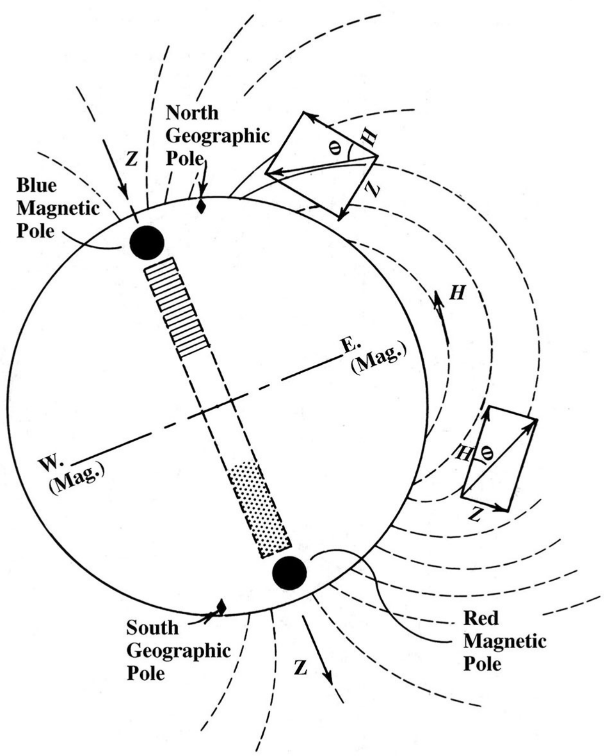


Figure 802a. Terrestrial magnetism.

Figure 802a illustrates the Earth and its surrounding magnetic field. The flux lines enter the surface of the Earth at different angles to the horizontal at different magnetic latitudes. This angle is called the **angle of magnetic dip**, θ, and increases from 0° at the magnetic equator to 90° at the magnetic poles. The total magnetic field is generally considered as having two components: H, the horizontal component; and Z, the vertical component. These components change as the angle θ changes, such that H is at its maximum at the magnetic equator and decreases in the direction of either pole, while Z is zero at the magnetic equator and increases in the direction of either pole.

Since the magnetic poles of the Earth do not coincide with the geographic poles, a compass needle in line with the Earth's magnetic field will not indicate true north, but magnetic north. The angular difference between the true meridian (great circle connecting the geographic poles) and the magnetic meridian (direction of the lines of magnetic flux) is called **variation**. This variation has different values at different locations on the Earth. These values of magnetic variation may be found on pilot charts and on the compass rose of navigational charts. Magnetic variations is sometimes called magnetic **declination**.

The poles are not geographically static. They are known to migrate slowly, so that variation for most areas undergoes a small annual change, the amount of which is also noted on charts.

More information on geomagnetism is available a the U.S. Geological Survey (USGS) website: http://geomag.usgs.gov/.

Figure 802b. USGS Geomagnetism Program.

803. The World Magnetic Model

The World Magnetic Model is a joint product of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defence Geographic Centre (DGC). The WMM was developed jointly by the National Geophysical Data Center (NGDC, Boulder CO, USA) (now the National Centers for Environmental Information (NCEI)) and the British Geological Survey (BGS, Edinburgh, Scotland).

Figure 803a. World Magnetic Model
https://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml

The World Magnetic Model is the standard model used by the U.S. Department of Defense, the U.K. Ministry of Defence, the North Atlantic Treaty Organization (NATO) and the International Hydrographic Organization (IHO), for navigation, attitude and heading referencing systems using the geomagnetic field. It is also used widely in civilian navigation and heading systems. The model, associated software, and documentation are distributed by NCEI on behalf of NGA. The model is produced at 5-year intervals, with the current model expiring on December 31, 2019. Figure 803b and Figure 803c show magnetic dip and variation (2015 epoch) for the world. Red contours are positive

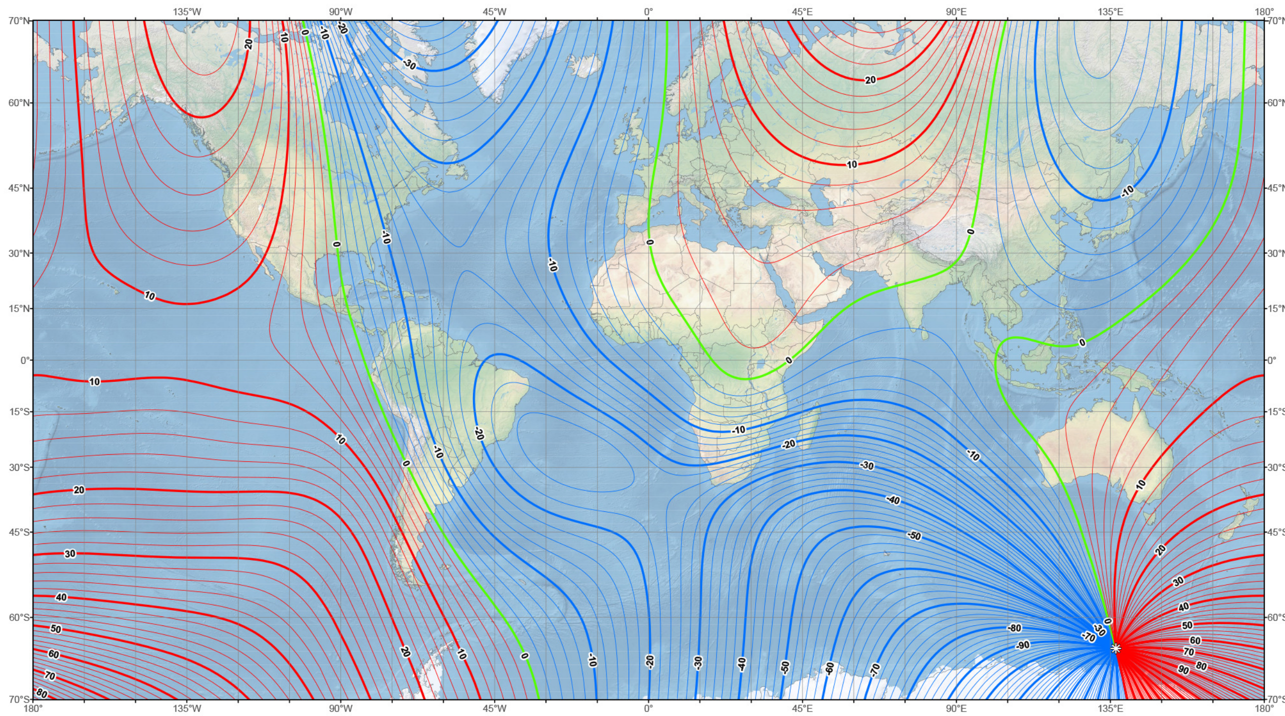


Figure 803b. Magnetic variation for the world (2015 Epoch).

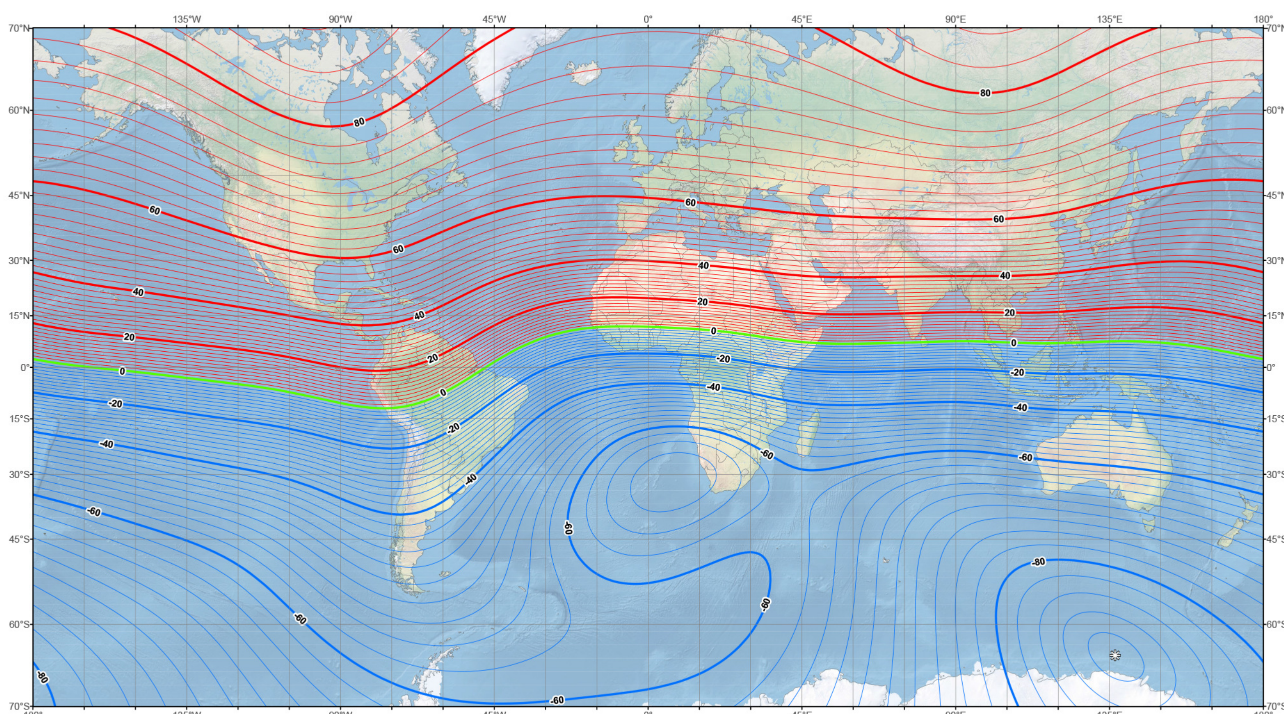


Figure 803c. Magnetic dip for the world (2015 Epoch).

or east, blue contours are negative or west and green is agonic or zero.

804. Ship's Magnetism

A ship under construction or repair will acquire permanent magnetism due to hammering and vibration while sitting stationary in the Earth's magnetic field. After launching, the ship will lose some of this original magnetism as a result of vibration and pounding in varying magnetic fields, and will eventually reach a more or less stable magnetic condition. The magnetism which remains is the **permanent magnetism** of the ship.

In addition to its permanent magnetism, a ship acquires **induced magnetism** when placed in the Earth's magnetic field. The magnetism induced in any given piece of soft iron is a function of the field intensity, the alignment of the soft iron in that field, and the physical properties and dimensions of the iron. This induced magnetism may add to, or subtract from, the permanent magnetism already present in the ship, depending on how the ship is aligned in the magnetic field. The softer the iron, the more readily it will be magnetized by the Earth's magnetic field, and the more readily it will give up its magnetism when removed from that field.

The magnetism in the various structures of a ship, which tends to change as a result of cruising, vibration, or aging, but which does not alter immediately so as to be properly termed induced magnetism, is called **subpermanent magnetism**. This magnetism, at any instant, is part of the ship's permanent magnetism, and consequently must be corrected by permanent magnet correctors. It is the principal cause of deviation changes on a magnetic compass. Subsequent reference to permanent magnetism will refer to the apparent permanent magnetism which includes the existing permanent and subpermanent magnetism.

A ship, then, has a combination of permanent, subpermanent, and induced magnetism. Therefore, the ship's apparent permanent magnetic condition is subject to change as a result of deperming, shocks, welding, and vibration. The ship's induced magnetism will vary with the Earth's magnetic field strength and with the alignment of the ship in that field.

805. Magnetic Adjustment

A narrow rod of soft iron, placed parallel to the Earth's horizontal magnetic field, H, will have a north pole induced in the end toward the north geographic pole and a south pole induced in the end toward the south geographic pole. This same rod in a horizontal plane, but at right angles to the horizontal Earth's field, would have no magnetism induced in it, because its alignment in the magnetic field precludes linear magnetization, if the rod is of negligible cross section. Should the rod be aligned in some horizontal direction between those headings which create maximum and zero induction, it would be induced by an amount which is a function of the angle of alignment. However, if a similar rod is placed in a vertical position in northern latitudes so as to be aligned with the vertical Earth's field Z, it will have a south pole induced at the upper end and a north pole induced at the lower end. These polarities of vertical induced magnetization will be reversed in southern latitudes.

The amount of horizontal or vertical induction in such rods, or in ships whose construction is equivalent to combinations of such rods, will vary with the intensity of H and Z, heading, and heel of the ship.

The magnetic compass must be corrected for the vessel's permanent and induced magnetism so that its operation approximates that of a completely nonmagnetic vessel. Ship's magnetic conditions create magnetic compass deviations and sectors of sluggishness and unsteadiness. **Deviation** is defined as deflection right or left of the magnetic meridian caused by magnetic properties of the vessel. Adjusting the compass consists of arranging magnetic and soft iron **correctors** near the compass so that their effects are equal and opposite to the effects of the magnetic material in the ship.

The total permanent magnetic field effect at the compass may be broken into three components, mutually 90° to each other (see Figure 805a).

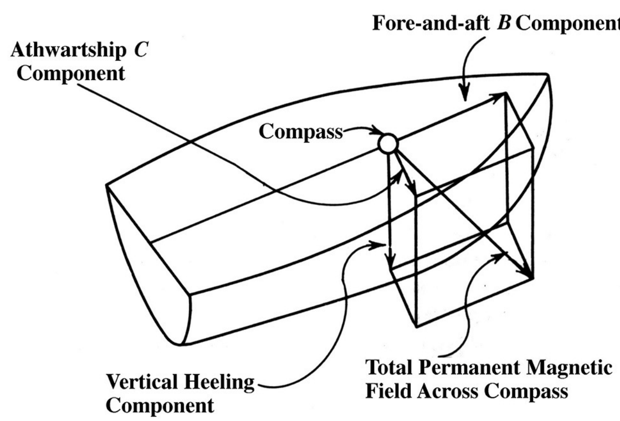


Figure 805a. Components of permanent magnetic field.

The vertical permanent component tilts the compass card, and, when the ship rolls or pitches, causes oscillating deflections of the card. Oscillation effects which accompany roll are maximum on north and south compass headings, and those which accompany pitch are maximum on east and west compass headings.

The horizontal B and C components of permanent magnetism cause varying deviations of the compass as the ship swings in heading on an even keel. Plotting these deviations against compass heading yields the sine and cosine curves shown in Figure 805b. These deviation curves are called semicircular curves because they reverse direction by 180°.

A vector analysis is helpful in determining deviations or the strength of deviating fields. For example, a ship as shown in Figure 805c on an east magnetic heading will subject its compass to a combination of magnetic effects; namely, the Earth's horizontal field H, and the deviating field B, at right angles to the field H. The compass needle will align itself in the resultant field which is represented by the vector sum of H and B, as shown. A similar analysis will reveal that the resulting directive force on the compass would be maximum on a north heading and minimum on a south heading because the deviations for both conditions are zero. The magnitude of the deviation caused by the permanent B magnetic field will vary with different values of H; hence, deviations resulting from permanent magnetic fields will vary with the magnetic latitude of the ship.

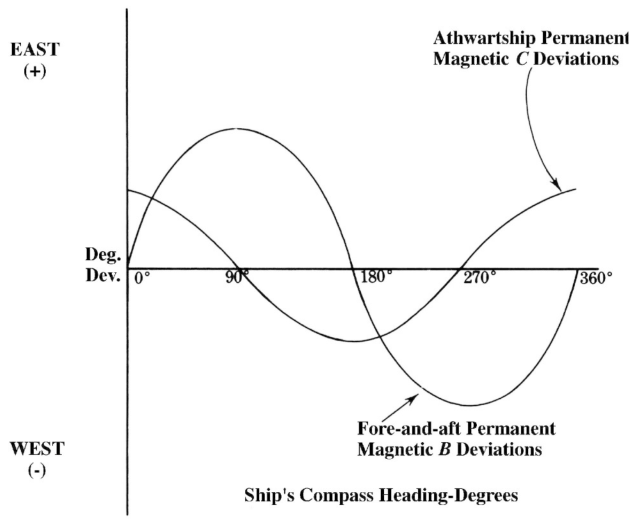


Figure 805b. Permanent magnetic deviation effects.

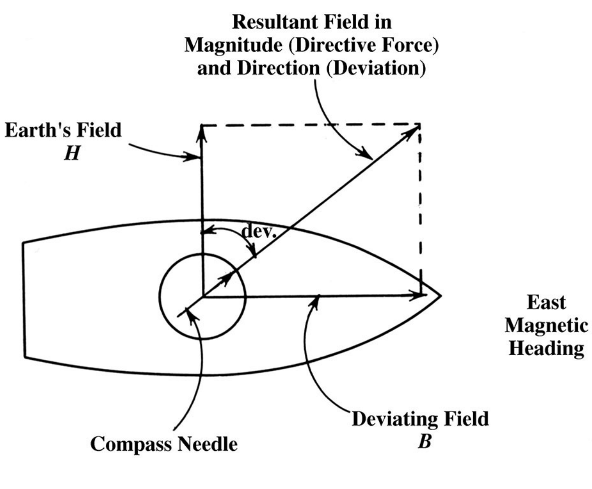


Figure 805c. General force diagram.

806. Effects of Induced Magnetism

Induced magnetism varies with the strength of the surrounding field, the mass of metal, and the alignment of the metal in the field. Since the intensity of the Earth's magnetic field varies over the Earth's surface, the induced magnetism in a ship will vary with latitude, heading, and heeling angle.

With the ship on an even keel, the resultant vertical induced magnetism, if not directed through the compass itself, will create deviations which plot as a semicircular deviation curve. This is true because the vertical induction changes magnitude and polarity only with magnetic latitude and heel, and not with heading of the ship. Therefore, as long as the ship is in the same magnetic latitude, its vertical induced pole swinging about the compass will produce the same effect on the compass as a permanent pole swinging about the compass.

The Earth's field induction in certain other unsymmetrical arrangements of horizontal soft iron create a constant A deviation curve. In addition to this magnetic A error, there are constant A deviations resulting from: (1) physical misalignments of the compass, pelorus, or gyro; (2) errors in calculating the Sun's azimuth, observing time, or taking bearings.

The nature, magnitude, and polarity of these induced effects are dependent upon the disposition of metal, the symmetry or asymmetry of the ship, the location of the binnacle, the strength of the Earth's magnetic field, and the angle of dip.

Certain heeling errors, in addition to those resulting from permanent magnetism, are created by the presence of both horizontal and vertical soft iron which experience changing induction as the ship rolls in the Earth's magnetic field. This part of the heeling error will change in magnitude proportional to changes of magnetic latitude of the ship. Oscillation effects associated with rolling are maximum on north and south headings, just as with the permanent magnetic heeling errors.

807. Adjustments and Correctors

Since some magnetic effects are functions of the vessel's magnetic latitude and others are not, each individual effect should be corrected independently. Furthermore, to make the corrections, we use (1) permanent magnet correctors to compensate for permanent magnetic fields at the compass, and (2) soft iron correctors to compensate for induced magnetism. The compass binnacle provides support for both the compass and its correctors. Typical large ship binnacles hold the following correctors:

1. Vertical permanent **heeling magnet** in the central vertical tube directly beneath the compass.
2. Fore-and-aft **B permanent magnets** in their trays.
3. Athwartship **C permanent magnets** in their trays.
4. Vertical soft iron **Flinders bar** in its external tube.
5. Soft iron **quadrantal spheres**.

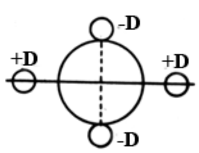
The heeling magnet is the only corrector which corrects for both permanent and induced effects. Therefore, it may need to be adjusted for changes in latitude if a vessel permanently changes its normal operating area. However, any movement of the heeling magnet will require readjustment of other correctors.

Fairly sophisticated magnetic compasses used on smaller commercial craft, larger yachts, and fishing vessels, may not have soft iron correctors or B and C permanent magnets. These compasses are adjusted by rotating magnets located inside the base of the unit, adjustable by small screws on the outside. A non-magnetic screwdriver is necessary to adjust these compasses. Occasionally one may find a permanent magnet corrector mounted near the compass, placed during the initial installation so as to remove a large, constant deviation before final adjustments are made. Normally, this remains in place for the life of the vessel.

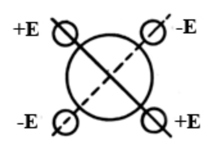
Figure 807 summarizes all the various magnetic conditions in a ship, the types of deviation curves they create, the correctors for each effect, and headings on which each corrector is adjusted. When adjusting the compass, always apply the correctors symmetrically and as far away from the compass as possible. This preserves the uniformity of magnetic fields about the compass needle.

Coefficient	Type deviation curve	Compass headings of maximum deviation	Causes of such errors	Correctors for such errors	Magnetic or compass headings on which to apply correctors
A	Constant.	Same on all.	Human-error in calculations _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ Physical-compass, gyro, pelorus alignment _ _ _ _ _ _ _ _ _ Magnetic-unsymmetrical arrangements of horiz. soft iron.	Check methods and calculations Check alignments Rare arrangement of soft iron rods.	Any.
B	Semicircular $\sin\phi$.	090° 270°	Fore-and-aft component of permanent magnetic field _ _ _ _ _ Induced magnetism in unsymmetrical vertical iron forward or aft of compass.	Fore-and-aft *B* magnets Flinders bar (forward or aft)	090° or 270°.
C	Semicircular $\cos\phi$.	000° 180°	Athwartship component of permanent magnetic field- - - - - - - Induced magnetism in unsymmetrical vertical iron port or starboard of compass.	Athwartship *C* magnets Flinders bar (port or starboard)	000° or 180°.
D	Quadrantral $\sin 2\phi$.	045° 135° 225° 315°	Induced magnetism in all symmetrical arrangements of horizontal soft iron.	Spheres on appropriate axis. (athwartship for +D) (fore and aft for -D) *See sketch a*	045°, 135°, 225°, or 315°.
E	Quadrantral $\cos 2\phi$.	000° 090° 180° 270°	Induced magnetism in all unsymmetrical arrangements of horizontal soft iron.	Spheres on appropriate axis. (port fwd.-stb'd for +E) (stb'd fwd.-port aft for -E) *See sketch b*	000°, 090°, 180°, or 270°.
Heeling	Oscillations with roll or pitch. Deviations with constant list.	000° 180° } roll 090° 270° } pitch	Change in the horizontal component of the induced or permanent magnetic fields at the compass due to rolling or pitching of the ship.	Heeling magnet (must be readjusted for latitude changes).	090° or 270° with dip needle. 000° or 180° while rolling.

$\text{Deviation} = A + B\sin\phi + C\cos\phi + D\sin 2\phi + E\cos 2\phi \quad (\phi = \text{compass heading})$



(Sketch a)



(Sketch b)

Figure 807. Summary of compass errors and adjustments.

Occasionally, the permanent magnetic effects at the location of the compass are so large that they overcome the Earth's directive force, H. This condition will not only create sluggish and unsteady sectors, but may even freeze the compass to one reading or to one quadrant, regardless of the heading of the ship. Should the compass become so frozen, the polarity of the magnetism which must be attracting the compass needles is indicated; hence, correction may be effected simply by the application of permanent magnet correctors to neutralize this magnetism. Whenever such adjustments are made, the ship should be steered on a heading such that the unfreezing of the compass needles will be immediately evident. For example, a ship whose compass is frozen to a north reading would require fore-and-aft B corrector magnets with the positive ends forward in order to neutralize the existing negative pole which attracted the compass. If made on an east heading, such an adjustment would be evident when the compass card was freed to indicate an east heading.

808. Reasons for Correcting Compass

There are several reasons for correcting the errors of a magnetic compass, even if it is not the primary directional reference:

1. It is easier to use a magnetic compass if the deviations are small.
2. Even known and fully compensated deviation introduces error because the compass operates sluggishly and unsteadily when deviation is present.

3. Even though the deviations are compensated for, they will be subject to appreciable change as a function of heel and magnetic latitude.

Theoretically, it doesn't matter what the compass error is as long as it is known. But a properly adjusted magnetic compass is more accurate in all sea conditions, easier to steer by, and less subject to transient deviations which could result in deviations from the ship's chosen course.

Therefore, if a magnetic compass is installed and meant to be relied upon, it behooves the navigator to attend carefully to its adjustment. Doing so is known as "swinging ship."

809. Adjustment Check-off List

While a professional compass adjuster will be able to obtain the smallest possible error curve in the shortest time, many ship's navigators adjust the compass themselves with satisfactory results. Whether or not a "perfect" adjustment is necessary depends on the degree to which the magnetic compass will be relied upon in day-to-day navigation. If the magnetic compass is only used as a backup compass, removal of every last possible degree of error may not be worthwhile. If the magnetic compass is the only steering reference aboard, as is the case with many smaller commercial craft and fishing vessels, it should be adjusted as accurately as possible.

Prior to getting underway to swing ship, the navigator must ensure that the process will proceed as expeditiously as possible by preparing the vessel and compass. The following tests and adjustment can be done at dockside, assuming that the compass has been installed and maintained properly. Initial installation and adjustment should be done by a professional compass technician during commissioning.

1. Check for bubbles in the compass bowl. Fluid may be added through the filling plug if necessary. Large bubbles indicate serious leakage, indicating that the compass should be taken to a professional compass repair facility for new gaskets. It is important to note that not all commercially available compass fluids are compatible with all compasses, especial compasses that were original alcohol-filled. Very early fluid-filled compasses from the late 1800's were filled with a mixture of alcohol and water. Compass oil became more commonly used after the 1940s. If unsure about the type of fluid, it is advisable to contact a professional before adding any.
2. Check for free movement of gimbals. Clean any dust or dirt from gimbal bearings and lubricate them as recommended by the maker.
3. Check for magnetization of the quadrantal spheres by moving them close to the compass and rotating them. If the compass needle moves more than 2 degrees, the spheres must be annealed to remove their magnetism. Annealing consists of heating the spheres to a dull red color in a non-magnetic area and allowing them to cool slowly to ambient temperature.
4. Check for magnetization of the Flinders bar by inverting it, preferably with the ship on an E/W heading. If the compass needle moves more than 2 degrees the Flinders bar must be annealed.
5. Synchronize the gyro repeaters with the master gyro so courses can be steered accurately.
6. Assemble past documentation relating to the compass and its adjustment. Have the ship's degaussing folder ready.
7. Ensure that every possible metallic object is stowed for sea. All guns, doors, booms, and other movable gear should be in its normal seagoing position. All gear normally turned on such as radios, radars, loudspeakers, etc. should be on while swinging ship.
8. Have the International Code flags Oscar-Quebec ready to fly.

Once underway to swing ship, the following procedures will expedite the process. Choose the best helmsman aboard and instruct him to steer each course as steadily and precisely as possible. Each course should be steered steadily for at least two minutes before any adjustments are made to remove Gaussin error. Be sure the gyro is set for the mean speed and latitude of the ship.

The navigator (or compass adjuster if one is employed) should have a pelorus and a table of azimuths prepared for checking the gyro, but the gyrocompass will be the primary steering reference. Normally the adjuster will request courses and move the magnets as he or she feels necessary, a process much more of an intuitive art than a science. If a professional adjuster is not available, use the following sequence:

1. If there is a sea running, steer course 000° and adjust the heeling magnet to decrease oscillations to a minimum.
2. Come to course 090°. When steady on course 090°, for at least two minutes, insert, remove, or move fore-and-aft B magnets to remove ALL deviation.
3. Come to a heading of 180°. Insert, remove, or move athwartships C magnets to remove ALL deviation.
4. Come to 270° and move the B magnets to remove one half of the deviation.
5. Come to 000° and move the C magnets to remove one half of the deviation.

6. Come to 045° (or any intercardinal heading) and move the quadrantal spheres toward or away from the compass to minimize any error.

7. Come to 135° (or any intercardinal heading 90° from the previous course) and move the spheres in or out to remove one half of the observed error.

8. Steer the ship in turn on each cardinal and intercardinal heading around the compass, recording the error at each heading called for on the deviation card. If plotted, the errors should plot roughly as a sine curve about the 0° line.

If necessary, repeat steps 1-8. There is no average error, for each ship is different, but generally speaking, errors of more than a few degrees, or errors which seriously distort the sine curve, indicate a magnetic problem which should be addressed.

Once the compass has been swung, tighten all fittings and carefully record the placement of all magnets and correctors. Finally, swing for residual degaussed deviations with the degaussing circuits energized and record the deviations on the deviation card. Post this card near the chart table for ready reference by the navigation team.

Once properly adjusted, the magnetic compass deviations should remain constant until there is some change in the magnetic condition of the vessel resulting from magnetic treatment, shock, vibration, repair, or structural changes. Transient deviations are discussed below.

810. Sources of Transient Error

The ship must be in seagoing trim and condition to properly compensate a magnetic compass. Any movement of large metal objects or the energizing of any electrical equipment in the vicinity of the compass can cause errors. If in doubt about the effect of any such changes, temporarily move the gear or cycle power to the equipment while observing the compass card while on a steady heading. Preferably this should be done on two different headings 90° apart, since the compass might be affected on one heading and not on another.

Some magnetic items which cause deviations if placed too close to the compass are as follows:

1. Movable guns or weapon loads
2. Magnetic cargo
3. Hoisting booms
4. Cable reels
5. Metal doors in wheelhouse
6. Chart table drawers
7. Movable gyro repeater
8. Windows and ports
9. Signal pistols racked near compass
10. Sound powered telephones
11. Magnetic wheel or rudder mechanism
12. Knives or tools near binnacle
13. Watches, wrist bands, spectacle frames
14. Hat grommets, belt buckles, metal pencils
15. Heating of smoke stack or exhaust pipes
16. Landing craft

Some electrical items which cause variable deviations if placed too close to the compass are:

1. Electric motors
2. Magnetic controllers
3. Gyro repeaters
4. Nonmarried conductors
5. Loudspeakers
6. Electric indicators
7. Electric welding
8. Large power circuits
9. Searchlights or flashlights
10. Electrical control panels or switches
11. Telephone headsets
12. Windshield wipers
13. Rudder position indicators, solenoid type
14. Minesweeping power circuits
15. Engine order telegraphs
16. Radar equipment
17. Magnetically controlled switches
18. Radio transmitters
19. Radio receivers
20. Voltage regulators

Another source of transient deviation is the **retentive error**. This error results from the tendency of a ship's structure to retain induced magnetic effects for short periods of time. For example, a ship traveling north for several days, especially if pounding in heavy seas, will tend to retain some fore-and-aft magnetism induced under these conditions. Although this effect is transient, it may cause slightly incorrect observations or adjustments. This same type of error occurs when ships are docked on one heading for long periods of time. A

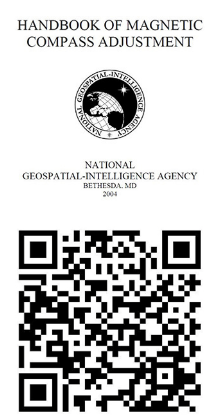


Figure 810. NGA Handbook of Magnetic Compass Adjustment (2004).
https://msi.nga.mil/MSISiteContent/StaticFiles/HoMCA.pdf

short shakedown, with the ship on other headings, will tend to remove such errors. A similar sort of residual magnetism is left in many ships if the degaussing circuits are not secured by the correct reversal sequence.

A source of transient deviation somewhat shorter in duration than retentive error is known as **Gaussin error**. This error is caused by eddy currents set up by a changing number of magnetic lines of force through soft iron as the ship changes heading. Due to these eddy currents, the induced magnetism on a given heading does not arrive at its normal value until about 2 minutes after changing course.

Deperming and other magnetic treatment will change the magnetic condition of the vessel and therefore require compass readjustment. The decaying effects of deperming can vary. Therefore, it is best to delay readjustment for several days after such treatment. Since the magnetic fields used for such treatments are sometimes rather large at the compass locations, the Flinders bar, compass, and related equipment should be removed from the ship during these operations.

For more information on magnetic adjustment see NGA's Handbook of Magnetic Compass Adjustments via the link provided in Figure 810.

DEGAUSSING (MAGNETIC SILENCING) COMPENSATION

811. Degaussing

A steel vessel has a certain amount of **permanent magnetism** in its "hard" iron and **induced magnetism** in its "soft" iron. Whenever two or more magnetic fields occupy the same space, the total field is the vector sum of the individual fields. Thus, near the magnetic field of a vessel, the total field is the combined total of the Earth's field and the vessel's field. Not only does the Earth's field affect the vessel's, the vessel's field affects the Earth's field in its immediate vicinity.

Since certain types of explosive mines are triggered by the magnetic influence of a vessel passing near them, a vessel may use a degaussing system to minimize its magnetic field. One method of doing this is to neutralize each component of the field with an opposite field produced by electrical cables coiled around the vessel. These cables, when energized, counteract the permanent magnetism of the vessel, rendering it magnetically neutral. This has severe effects on magnetic compasses.

A unit sometimes used for measuring the strength of a magnetic field is the **gauss**. Reducing of the strength of a magnetic field decreases the number of gauss in that field. Hence, the process is called **degaussing**.

The magnetic field of the vessel is completely altered when the degaussing coils are energized, introducing large deviations in the magnetic compass. This deviation can be removed by introducing an equal and opposite force with energized coils near the compass. This is called **compass compensation**. When there is a possibility of confusion with compass adjustment to neutralize the effects of the natural magnetism of the vessel, the expression **degaussing compensation** is used. Since compensation may not be perfect, a small amount of deviation due to degaussing may remain on certain headings. This is the reason for swinging the ship with degaussing off and again with it on, and why there are two separate columns in the deviation table.

812. A Vessel's Magnetic Signature

A simplified diagram of the distortion of the Earth's magnetic field in the vicinity of a steel vessel is shown in Figure 812a. The field strength is directly proportional to the line spacing density. If a vessel passes over a device for detecting and recording the strength of the magnetic field, a certain pattern is traced. Figure 812b shows this pattern. Since the magnetic field of each vessel is different, each produces a distinctive trace. This distinctive trace is referred to as the vessel's **magnetic signature**.

Several **degaussing stations** have been established in major ports to determine magnetic signatures and recommend the current adjustments needed in the various degaussing coils to render the vessel magnetically neutral. Since a vessel's induced magnetism varies with heading and magnetic latitude, the current settings of the coils may sometimes need to be changed. A **degaussing folder** is provided to the vessel to indicate these changes and to document other pertinent information.

A vessel's permanent magnetism changes somewhat with time and the magnetic history of the vessel. Therefore, the data in the degaussing folder should be checked periodically at the magnetic station.

813. Degaussing Coils

For degaussing purposes, the total field of the vessel is divided into three components: (1) vertical, (2) horizontal fore-and-aft, and (3) horizontal athwartships. The positive (+) directions are considered downward, forward, and to port, respectively. These are the normal directions for a vessel headed north or east in north latitude.

Each component is opposed by a separate degaussing field just strong enough to neutralize it. Ideally, when this has been done, the Earth's field passes through the vessel smoothly and without distortion. The opposing degaussing fields are produced by direct current flowing in coils of wire. Each of the degaussing coils is placed so that the field it produces is directed to oppose one component of the

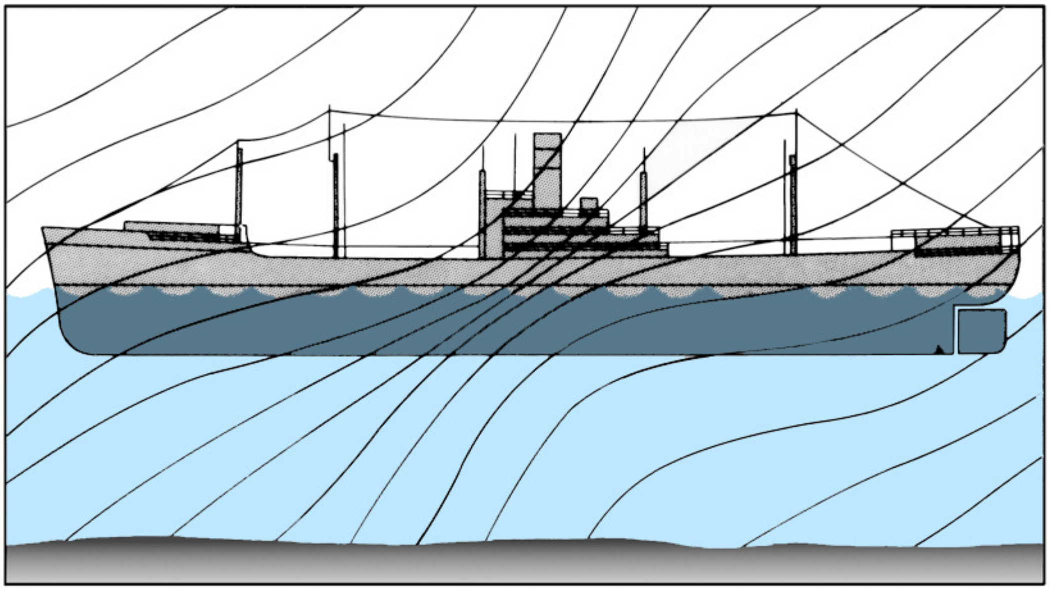


Figure 812a. Simplified diagram of distortion of Earth's magnetic field in the vicinity of a steel vessel.

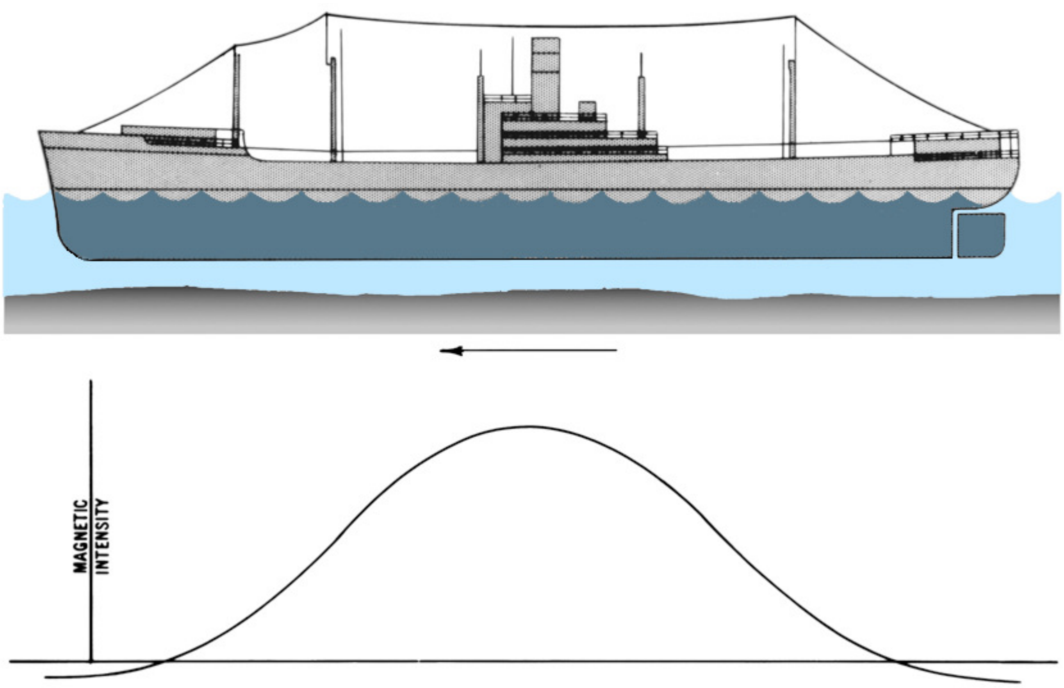


Figure 812b. A simplified signature of a vessel of Figure 812a.

ship's field.

The number of coils installed depends upon the magnetic characteristics of the vessel, and the degree of safety desired. The ship's permanent and induced magnetism may be neutralized separately so that control of induced magnetism can be varied as heading and latitude change, without disturbing the fields opposing the vessel's permanent field. The principal coils employed are the following:

Main (M) coil. The M coil is horizontal and completely encircles the vessel, usually at or near the waterline. Its function is to oppose the vertical component of the vessel's combined permanent and induced fields. Generally the induced field predominates. Current in the M-coil is varied or reversed according to the change of the induced component of the vertical field with latitude.

Forecastle (F) and **quarterdeck (Q) coils**. The F and Q coils are placed horizontally just below the forward and after thirds (or quarters), respectively, of the weather deck. These coils, in which current can be individually adjusted, remove much of the fore-and-aft component of the ship's permanent and induced fields. More commonly, the combined F and Q coils consist of two parts; one part the FP and QP coils, to take care of the permanent fore-and-aft field, and the other part, the FI and QI coils, to neutralize the induced fore-and-aft field. Generally, the forward and after coils of each type are connected in series, forming a split-coil installation and designated FP-QP coils and FI-QI coils. Current in the FP-QP coils is generally constant, but in the FI-QI coils is varied according to the heading and magnetic latitude of the vessel. In split-coil installations, the coil designations are often called simply the P-coil and I-coil.

Longitudinal (L) coil. Better control of the fore-and-aft components, but at greater installation expense, is provided by placing a series of vertical, athwartship coils along the length of the ship. It is the field, not the coils, which is longitudinal. Current in an L coil is varied as with the FI-QI coils. It is maximum on north and south headings, and zero on east and west headings.

Athwartship (A) coil. The A coil is in a vertical fore-and-aft plane, thus producing a horizontal athwartship field which neutralizes the athwartship component of the vessel's field. In most vessels, this component of the permanent field is small and can be ignored. Since the A-coil neutralizes the induced field, primarily, the current is changed with magnetic latitude and with heading, maximum on east or west headings, and zero on north or south headings.

The strength and direction of the current in each coil is indicated and adjusted at a control panel accessible to the navigator. Current may be controlled directly by rheostats at the control panel or remotely by push buttons which operate rheostats in the engine room.

Appropriate values of the current in each coil are determined at a degaussing station, where the various currents are adjusted until the vessel's magnetic signature is made as flat as possible. Recommended current values and directions for all headings and magnetic latitudes are set forth in the vessel's degaussing folder. This document is normally kept by the navigator, who must see that the recommended settings are maintained whenever the degaussing system is energized.

814. Securing The Degaussing System

Unless the degaussing system is properly secured, residual magnetism may remain in the vessel. During degaussing compensation and at other times, as recommended in the degaussing folder, the "reversal" method is used. The steps in the reversal process are as follows:

1. Start with maximum degaussing current used since the system was last energized.
2. Decrease current to zero and increase it in the opposite direction to the same value as in step 1.
3. Decrease the current to zero and increase it to three-fourths maximum value in the original direction.
4. Decrease the current to zero and increase it to one-half maximum value in the opposite direction.
5. Decrease the current to zero and increase it to one-fourth maximum value in the original direction.
6. Decrease the current to zero and increase it to one-eighth maximum value in the opposite direction.
7. Decrease the current to zero and open switch.

815. Magnetic Treatment Of Vessels

In some instances, degaussing can be made more effective by changing the magnetic characteristics of the vessel by a process known as **deperming**. Heavy cables are wound around the vessel in an athwartship direction, forming vertical loops around the longitudinal axis of the vessel. The loops are run beneath the keel, up the sides, and over the top of the weather deck at closely spaced equal intervals along the entire length of the vessel. Predetermined values of direct current are then passed through the coils. When the desired magnetic characteristics have been acquired, the cables are removed.

A vessel which does not have degaussing coils, or which has a degaussing system that is inoperative, can be given some temporary protection by a process known as **flashing**. A horizontal coil is placed around the outside of the vessel and energized with large predetermined values of direct current. When the vessel has acquired a vertical field of permanent magnetism of the correct magnitude and polarity to reduce to a minimum the resultant field below the vessel for the particular magnetic latitude involved, the cable is removed. This type protection is not as satisfactory as that provided by degaussing coils because it is not adjustable for various headings and magnetic latitudes, and also because the vessel's magnetism slowly readjusts following treatment.

During magnetic treatment all magnetic compasses and Flinders bars should be removed from the ship. Permanent adjusting magnets and quadrantal correctors are not materially affected, and need not be removed. If it is impractical to remove a compass, the cables used for magnetic treatment should be kept as far as practical from it.

816. Degaussing Effects

The degaussing of ships for protection against magnetic influence mines creates additional effects upon magnetic compasses, which are somewhat different from the permanent and induced magnetic effects. The degaussing effects are electromagnetic, and depend on:

1. Number and type of degaussing coils installed.
2. Magnetic strength and polarity of the degaussing coils.
3. Relative location of the different degaussing coils

with respect to the binnacle.

4. Presence of masses of steel, which would tend to concentrate or distort magnetic fields in the vicinity of the binnacle.
5. The fact that degaussing coils are operated intermittently, with variable current values, and with different polarities, as dictated by necessary degaussing conditions.

817. Degaussing Compensation

The magnetic fields created by the degaussing coils would render the vessel's magnetic compasses useless unless compensated. This is accomplished by subjecting the compass to compensating fields along three mutually perpendicular axes. These fields are provided by small **compensating coils** adjacent to the compass. In nearly all installations, one of these coils, the **heeling coil**, is horizontal and on the same plane as the compass card, providing a vertical compensating field. Current in the heeling coil is adjusted until the vertical component of the total degaussing field is neutralized. The other compensating coils provide horizontal fields perpendicular to each other. Current is varied in these coils until their resultant field is equal and opposite to the horizontal component of the degaussing field. In early installations, these horizontal fields were directed fore-and-aft and athwartships by placing the coils around the Flinders bar and the quadrantal spheres. Compactness and other advantages are gained by placing the coils on perpendicular axes extending 045°-225° and 315°-135° relative to the heading. A frequently used compensating installation, called the **type K**, is shown in Figure 817. It consists of a heeling coil extending completely around the top of the binnacle, four **intercardinal coils**, and three control boxes. The intercardinal coils are named for their positions relative to the compass when the vessel is on a heading of north, and also for the compass headings on which the current in the coils is adjusted to the correct amount for compensation. The NE-SW coils operate together as one set, and the NW-SE coils operate as another. One control box is provided for each set, and one for the heeling coil.

The compass compensating coils are connected to the power supply of the degaussing coils, and the currents passing through the compensating coils are adjusted by series resistances so that the compensating field is equal to the degaussing field. Thus, a change in the degaussing currents is accompanied by a proportional change in the compensating currents. Each coil has a separate winding for each degaussing circuit it compensates.

Degaussing compensation is carried out while the vessel is moored at the shipyard where the degaussing coils are installed. This process is usually carried out by civilian professionals, using the following procedure:

Step 1. The compass is removed from its binnacle and a dip needle is installed in its place. The M coil and heeling coil are then energized, and the current in the heeling coil is adjusted until the dip needle indicates the correct value for the magnetic latitude of the vessel. The system is then secured by the reversing process.

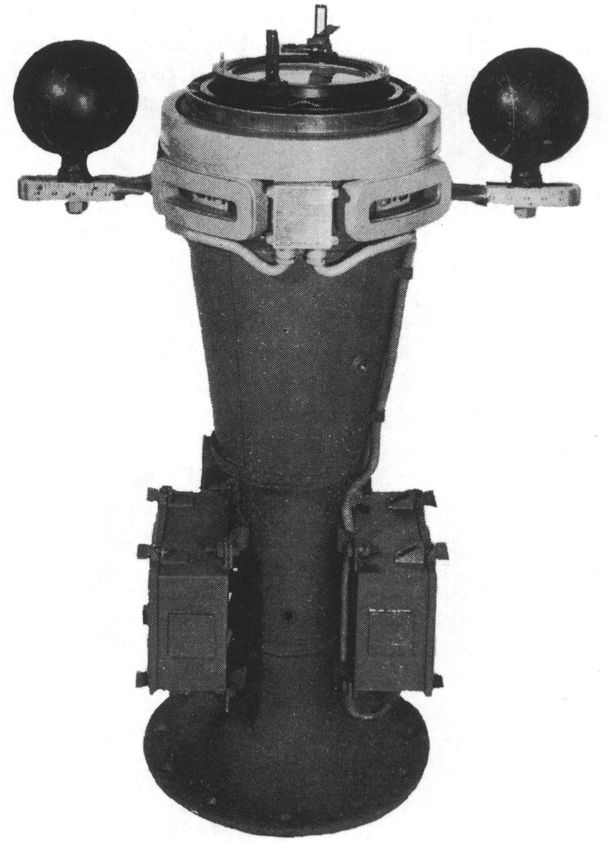


Figure 817. Type K degaussing compensation installation.

Step 2. The compass is replaced in the binnacle. With auxiliary magnets, the compass card is deflected until the compass magnets are parallel to one of the compensating coils or set of coils used to produce a horizontal field. The compass magnets are then perpendicular to the field produced by that coil. One of the degaussing circuits producing a horizontal field, and its compensating winding, are then energized, and the current in the compensating winding is adjusted until the compass reading returns to the value it had before the degaussing circuit was energized. The system is then secured by the reversing process. The process is repeated with each additional circuit used to create a horizontal field. The auxiliary magnets are then removed.

Step 3. The auxiliary magnets are placed so that the compass magnets are parallel to the other compensating coils or set of coils used to produce a horizontal field. The procedure of step 2 is then repeated for each circuit producing a horizontal field.

When the vessel gets under way, it proceeds to a suitable maneuvering area. The vessel is then steered so that the compass magnets are parallel first to one compensating coil or set of coils, and then the other. Any needed adjustment is made in the compensating circuits to reduce the error to a minimum. The vessel is then swung for residual deviation, first with degaussing off and then with degaussing on, and the correct current settings determined for each heading at the magnetic latitude of the vessel. From the values thus obtained, the "DG OFF" and "DG ON" columns of the deviation table are filled in. If the results indicate satisfactory compensation, a record is made of the degaussing coil settings and the resistance, voltages, and currents in the compensating coil circuits. The control boxes are then secured.

Under normal operating conditions, the settings do not need to be changed unless changes are made in the degaussing system, or unless an alteration is made in the length of the Flinders bar or the setting of the quadrantal spheres. However, it is possible for a ground to occur in the coils or control box if the circuits are not adequately protected from moisture. If this occurs, it should be reflected by a change in deviation with degaussing on, or by a decreased installation resistance. Under these conditions, compensation should be done again. If the compass will be used with degaussing on before the ship can be returned to a shipyard where the compensation can be made by experienced personnel, the compensation should be made at sea on the actual headings needed, rather than by deflection of the compass needles by magnets. More complete information related to this process is given in the degaussing folder.

If a vessel has been given magnetic treatment, its magnetic properties have changed, necessitating readjustment of each magnetic compass. This is best delayed for several days to permit the magnetic characteristics of the vessel to settle. If compensation cannot be delayed, the vessel should be swung again for residual deviation after a few days. Degaussing compensation should not be made until after compass adjustment has been completed.

GYROCOMPASSES

818. Principles of the Gyroscope

A gyroscope consists of a spinning wheel or rotor contained within gimbals which permit movement about three mutually perpendicular axes, known as the **horizontal axis**, the **vertical axis**, and the **spin axis**. When spun rapidly, assuming that friction is not considered, the gyroscope develops **gyroscopic inertia**, tending to remain spinning in the same plane indefinitely. The amount of gyroscopic inertia depends on the angular velocity, mass, and radius of the wheel or rotor.

When a force is applied to change alignment of the spin axis of a gyroscope, the resultant motion is perpendicular to the direction of the force. This tendency is known as precession. A force applied to the center of gravity of the gyroscope will move the entire system in the direction of the force. Only a force that tends to change the axis of rotation produces precession.

If a gyroscope is placed at the equator with its spin axis pointing east-west, as the Earth turns on its axis, gyroscopic inertia will tend to keep the plane of rotation constant. To the observer, it is the gyroscope which is seen to rotate, not the Earth. This effect is called the horizontal earth rate, and is maximum at the equator and zero at the poles. At points between, it is equal to the cosine of the latitude.

If the gyro is placed at a geographic pole with its spin axis horizontal, it will appear to rotate about its vertical axis. This is the vertical earth rate. At all points between the equator and the poles, the gyro appears to turn partly about its horizontal and partly about its vertical axis, being affected by both horizontal and vertical earth rates. In order to visualize these effects, remember that the gyro, at whatever latitude it is placed, is remaining aligned in space while the Earth moves beneath it.

819. Gyrocompass Operation

The gyrocompass depends upon four natural phenomena: gyroscopic inertia, precession, Earth's rotation, and gravity. To make a gyroscope into a gyrocompass, the wheel or rotor is mounted in a sphere, called the gyrosphere, and the sphere is then supported in a vertical ring. The whole is mounted on a base called the phantom. The gyroscope in a gyrocompass can be pendulous or non-pendulous, according to design. The rotor may weigh as little as half a kilogram to over 25 kg.

To make it seek and maintain true north, three things are necessary. First, the gyro must be made to stay on the plane of the meridian. Second, it must be made to remain horizontal. Third, it must stay in this position once it reaches horizontal regardless what the vessel on which it is mounted does or where it goes on the Earth. To make it seek the meridian, a weight is added to the bottom of the vertical ring, causing it to swing on its vertical axis, and thus seek to align itself horizontally. It will tend to oscillate, so a second weight is added to the side of the sphere in which the rotor is contained, which dampens the oscillations until the gyro stays on the meridian. With these two weights, the only possible position of equilibrium is on the meridian with its spin axis horizontal.

To make the gyro seek north, a system of reservoirs filled with mercury, known as mercury ballistics, is used to apply a force against the spin axis. The ballistics, usually four in number, are placed so that their centers of gravity exactly coincide with the CG of the gyroscope. Precession then causes the spin axis to trace an ellipse, one ellipse taking about 84 minutes to complete. (This is the period of oscillation of a pendulum with an arm equal to the radius of the Earth.) To dampen this oscillation the force is applied, not in the vertical plane, but slightly to the east of the vertical plane. This causes the spin axis to trace a spiral instead of an ellipse and eventually settle on the meridian pointing north.

820. Gyrocompass Errors

The total of the all the combined errors of the gyrocompass is called **gyro error** and is expressed in degrees E or W, just like variation and deviation. But gyro error, unlike magnetic compass error, and being independent of Earth's magnetic field, will be constant in one direction; that is, an error of one degree east will apply to all bearings all around the compass.

The errors to which a gyrocompass is subject are speed error, latitude error, ballistic deflection error, ballistic damping error, quadrantal error, and gimballing error. Additional errors may be introduced by a malfunction or incorrect alignment with the centerline of the vessel.

Speed error is caused by the fact that a gyrocompass only moves directly east or west when it is stationary (on the rotating Earth) or placed on a vessel moving exactly east or west. Any movement to the north or south will cause the compass to trace a path which is actually a function of the speed of advance and the amount of northerly or southerly heading. This causes the compass to tend to settle a bit off true north. This error is westerly if the vessel's course is northerly, and easterly if the course is southerly. Its magnitude depends on the vessel's speed, course, and latitude. This error can be corrected internally by means of a cosine cam mounted on the underside of the azimuth gear, which removes most of the error. Any remaining error is minor in amount and can be disregarded.

Tangent latitude error is a property only of gyros with mercury ballistics, and is easterly in north latitudes and westerly in south latitudes. This error is also corrected internally, by offsetting the lubber's line or with a small movable weight attached to the casing.

Ballistic deflection error occurs when there is a marked change in the north-south component of the speed. East-west accelerations have no effect. A change of course or speed also results in speed error in the opposite direction, and the two tend to cancel each other if the compass is properly designed. This aspect of design involves slightly offsetting the ballistics according to the operating latitude, upon which the correction is dependent. As latitude changes, the error becomes apparent, but can be minimized by adjusting the offset.

Ballistic damping error is a temporary oscillation introduced by changes in course or speed. During a change in course or speed, the mercury in the ballistic is subjected to centrifugal and acceleration/deceleration forces. This causes a torquing of the spin axis and subsequent error in the compass reading. Slow changes do not introduce enough error to be a problem, but rapid changes will. This error is counteracted by changing the position of the ballistics so that the true vertical axis is centered, thus not subject to error, but only when certain rates of turn or acceleration are exceeded.

Quadrantal error has two causes. The first occurs if the center of gravity of the gyro is not exactly centered in the phantom. This causes the gyro to tend to swing along its heavy axis as the vessel rolls in the sea. It is minimized by adding weight so that the mass is the same in all directions from the center. Without a long axis of weight, there is no tendency to swing in one particular direction. The second source of quadrantal error is more difficult to eliminate. As a vessel rolls in the sea, the apparent vertical axis is displaced, first to one side and then the other. The vertical axis of the gyro tends to align itself with the apparent vertical. On northerly or southerly courses, and on easterly or westerly courses, the compass precesses equally to both sides and the resulting error is zero. On intercardinal courses, the N-S and E-W precessions are additive, and a persistent error is introduced, which changes direction in different quadrants. This error is corrected by use of a second gyroscope called a floating ballistic, which stabilizes the mercury ballistic as the vessel rolls, eliminating the error. Another method is to use two gyros for the directive element, which tend to precess in opposite directions, neutralizing the error.

Gimballing error is caused by taking readings from the compass card when it is tilted from the horizontal plane. It applies to the compass itself and to all repeaters. To minimize this error, the outer ring of the gimbal of each repeater should be installed in alignment with the fore-and-aft line of the vessel. Of course, the lubber's line must be exactly centered as well.

821. Using the Gyrocompass

Since a gyrocompass is not influenced by magnetism, it is not subject to variation or deviation. Any error is constant and equal around the horizon, and can often be reduced to less than one degree, thus effectively eliminating it altogether. Unlike a magnetic compass, it can output a signal to repeaters spaced around the vessel at critical positions.

But it also requires a constant source of stable electrical power, and if power is lost, it requires several hours to settle on the meridian again before it can be used. This period can be reduced by aligning the compass with the meridian before turning on the power.

The directive force of a gyrocompass depends on the amount of precession to which it is subject, which in turn is dependent on latitude. Thus the directive force is maximum at the equator and decreases to zero at the poles. Vessels operating in high latitudes must construct error curves based on latitudes because the errors at high latitudes eventually overcome the ability of the compass to correct them.

The gyrocompass is typically located below decks as close as possible to the center of roll, pitch and yaw of the ship, thus minimizing errors caused by the ship's motion. Repeaters are located at convenient places throughout the ship, such as at the helm for steering, on the bridge wings for taking bearings, in after steering for emergency steering, and other places. The output can also be used to drive course recorders, autopilot systems, plotters, fire control systems, and stabilized radars. The repeaters should be checked regularly against the master to ensure they are all in alignment. The repeaters on the bridge wing used for taking bearings will likely be equipped with removable bearing circles, azimuth circles, and telescopic alidades, which allow one to sight a distant object and see its exact gyrocompass bearing.

ELECTRONIC COMPASSES

822. New Direction Sensing Technologies

The magnetic compass has considerable limitations, chiefly that of being unable to isolate the earth's magnetic field from all others close enough to influence it. It also indicates magnetic north, whereas the mariner is most interested in true north. Most of the work involved with compensating a traditional magnetic compass involves neutralizing magnetic influences other than the Earth's, a complicated and inexact process often involving more art than science. Residual error is almost always present even after compensation. Degaussing complicates the situation immensely.

The electro-mechanical gyrocompass has been the standard steering and navigational compass since the early 20th century, and has provided several generations of mariners a stable and reliable heading and bearing reference. However, it too has limitations: It is a large, expensive, heavy, sensitive device that must be mounted according to rather strict limitations. It requires a stable and uninterrupted supply of electrical power; it is sensitive to shock, vibration, and environmental changes; and it needs several hours to settle after initialization.

Fortunately, several new technologies have been developed which promise to greatly reduce or eliminate the complications brought on by the limitations of both the mechanical gyroscope and traditional magnetic compasses. Sometimes referred to as "electronic compasses," the digital flux gate magnetic compass and the ring laser gyrocompass are two such devices. They have the following advantages:

1. Solid state electronics, no moving parts
2. Operation at very low power
3. Easy backup power from independent sources
4. Standardized digital output
5. Zero friction, drift, or wear
6. Compact, lightweight, and inexpensive
7. Rapid start-up and self-alignment
8. Low sensitivity to vibration, shock, and temperature changes
9. Self-correcting

Both types are being installed in many vessels as the primary directional reference, enabling the decommissioning of the traditional magnetic compasses and the avoidance of periodic compensation and maintenance.

823. The Flux Gate Compass

The most widely used sensor for digital compasses is the flux-gate magnetometer, developed around 1928. Initially it was used for detecting submarines, for geophysical prospecting, and airborne mapping of Earth's magnetic fields.

The most common type, called the second harmonic device, incorporates two coils, a primary and a secondary, both wrapped around a single highly permeable ferromagnetic core. In the presence of an external magnetic field, the core's magnetic induction changes. A signal applied to the primary winding causes the core to oscillate. The secondary winding emits a signal that is induced through the core from the primary winding. This induced signal is affected by changes in the permeability of the core and appears as an amplitude variation in the output of the sensing coil. The signal is then demodulated with a phase-sensitive detector and filtered to retrieve the magnetic field value. After being converted to a standardized digital format, the data can be output to numerous remote devices, including steering compasses, bearing compasses, emergency steering stations, and autopilots.

Since the influence of a ship's inherent magnetism is inversely proportional to the square of the distance to the compass, it is logical that if the compass could be located at some distance from the ship, the influence of the ship's magnetic field could be greatly reduced. One advantage of the flux gate compass is that the sensor can be located remotely from the readout device, allowing it to be placed at a position as far as possible from the hull and its contents, such as high up on a mast, the ideal place for most vessels.

A further advantage is that the digital signal can be processed mathematically, and algorithms written which can correct for observed deviation once the deviation table has been determined. Further, the "table," in digital format, can be found by merely steering the vessel in a full circle. Algorithms then determine and apply corrections that effectively flatten the usual sine wave pattern of deviation. The theoretical result is zero observed compass deviation.

Should there be an index error (which has the effect of skewing the entire sine wave below or above the zero degree axis of the deviation curve) this can be corrected with an index correction applied to all the readings. This problem is largely confined to asymmetric installations such as aircraft carriers. Similarly, a correction for variation can be applied, and with GPS input (so the system knows where it is with respect to the isogonic map) the variation correction can be applied automatically, thus rendering the output in true degrees, corrected for both deviation and variation.

It is important to remember that a flux gate compass is still a magnetic compass, and that it will be influenced by large changes to the ship's magnetic field. Compensation should be accomplished after every such change. Fortunately, as noted, compensation involves merely steering the vessel in a circle in accordance with the manufacturer's recommendations.

Flux-gate compasses from different manufacturers share some similar operational modes. Most of them will have the following:

SET COURSE MODE: A course can be set and "remembered" by the system, which then provides the helmsman a graphic steering aid, enabling him to see if the ship's head is right or left of the set course, as if on a digital "highway." Normal compass operation continues in the background.

DISPLAY RESPONSE DAMPING: In this mode, a switch is used to change the rate of damping and update of the display in response to changes in sea condition and vessel speed.

AUTO-COMPENSATION: This mode is used to determine the deviation curve for the vessel as it steams in a complete circle. The system will then automatically compute correction factors to apply around the entire compass, resulting in zero deviation at any given heading. This should be done after every significant change in the magnetic signature of the ship, and within 24 hours of entering restricted waters.

CONTINUOUS AUTO-COMPENSATION: This mode, which should normally be turned OFF in restricted waters and ON at sea, runs the compensation algorithm each time the ship completes a 360 degree turn in two minutes. A warning will flash on the display in the OFF mode.

PRE-SET VARIATION: In effect an index correction, pre-set variation allows the application of magnetic variation to the heading, resulting in a true output (assuming the unit has been properly compensated and aligned). Since variation changes according to one's location on the Earth, it must be changed periodically to agree with the charted variation unless GPS input is provided. The GPS position input is used in an algorithm which computes the variation for the area and automatically corrects the readout.

U.S. Naval policy approves the use of flux gate compasses and the lay-up, but not the removal of the traditional binnacle mounted compass, which should be clearly marked as "Out of Commission" once an approved flux gate compass has been properly installed and tested.

824. Optical Gyroscopes

Optical gyroscope use can be classified under two major types: ring laser gyroscope (RLG) and fiber optic gyroscope (FOG). Both of these sensors make use of French Physicist Georges Sagnac's observation of rotation relative to inertial space thus bearing the name, Sagnac Effect. This principle states that if two beams of light are sent in opposite directions around a "ring" or polyhedron and steered so as to meet and combine, a standing wave will form around the ring. If the wave is observed from any point, and that point is then moved along the perimeter of the ring, the wave form will change in direct relationship to the direction and velocity of movement. While Sagnac's work was in pursuit of identifying the "ether" that was postulated in the late 19th century as the medium that supported the propagation of light waves, the effect that he predicted and measured was found to be rooted in general relativity. Sagnac is given significant credit, because he was the first person to report the experimental observation for a polygonal interferometer mounted on a turn-table. The practical realization of a Sagnac interferometer as a rotation sensor came only after the invention of the laser and other optical components. The Sagnac interferometer can be implemented in a resonant cavity as in the case of the RLG or in a non-resonant interferometer configuration of which the commercially available FOG is an example. While it is true that a FOG can be configured as a resonant cavity, this type of device has not yet achieved commercial success and will not be described herein.

825. The Ring Laser Gyrocompass

The ring laser had its beginnings in England, where in the 1890's two scientists, Joseph Larmor and Sir Oliver Lodge (also one of the pioneers of radio), debated the possibility of measuring rotation by a ring interferometer. Following Sagnac's 1913 observation. It wasn't until 1963 that D. T. M. Davis Jr. and W. Macek of Sperry-Rand Corporation tested and refined the concept into a useful research device. Initially, mirrors were used to direct light around a square or rectangular pattern. But such mirrors must be made and adjusted to exceptionally close tolerances to allow useful output, and must operate in a vacuum for best effect. Multilayer dielectric mirrors with a reflectivity of 99.9999 percent were developed. The invention of laser light sources and fiber-optics has enabled the production of small, light, and dependable ring laser gyros. Mirror-based devices continue to be used in physics research.

The ring laser gyrocompass (RLG) operates by measuring laser-generated light waves traveling around a fiber-optic ring. A beam splitter divides a beam of light into two counter-rotating waves, which then travel around the fiber-optic ring in opposite directions. The beams are then recombined and sent to an output detector. In the absence of rotation, the path lengths will be the same and the beams will recombine in phase. If the device has rotated, there will be a difference in the length of the paths of the two beams, resulting in a detectable phase difference in the combined signal. The signal will vary in amplitude depending on the amount of the phase shift. The amplitude is thus a measurement of the phase shift, and consequently, the rotation rate. This signal is processed into a digital readout in degrees. This readout, being digital, can then be sent to a variety of devices which need heading information, such as helm, autopilot, and electronic chart systems.

A single ring laser gyroscope can be used to provide a one-dimensional rotational reference, exactly what a compass needs. The usefulness of ring laser gyrocompasses is clear in that they share many of the same characteristics of flux gate compasses. They are compact, light, inexpensive, accurate, dependable, and robust. The ring laser device is also unaffected by magnetic influences that would certainly impact the traditional compass, and even such that might adversely affect a remotely mounted flux gate compass.

Ring laser gyroscopes can also serve as the stable elements in an inertial guidance system, using three gyros to represent the three degrees of freedom, thus providing both directional and position information. The principle of operation is the same as for mechanical inertial navigation devices, in that a single gyro can measure any rotation about its own axis. This implies that its orientation in space about its own axis will be known at all times. Three gyros arranged along three axes each at 90 degrees to the others can measure accelerations in three dimensional space, and thus track movement over time.

Inertial navigation systems based on ring lasers have been used in aircraft for a number of years, and are becoming increasingly common in maritime applications. Uses include navigation, radar and fire control systems, precise weapons stabilization, and stabilization of directional sensors such as satellite antennas.

826. The Fiber Optic Gyro

A non-resonant Sagnac interferometer is used as the basis of what is referred to as the interferometric fiber optic gyro (IFOG) often shortened to simply FOG. Resonant fiber optic gyros have been developed but at this time have not become commercially practical.

The development of the FOG required its own enabling technology, namely low loss, single mode optical fibers that became available in the mid-1970s. Vali and Shorthill first proposed the fiber optic gyro in 1975. The FOG is composed of a light source, a coupler, a fiber coil and a detector. Light is launched from the source and coupled through a fiber optic coil in both the clockwise and counter-clockwise directions. Based on the Sagnac effect, the optical path seen by the two beams interfere and the intensity detected is a function of the phase difference and hence the angular rate of the gyro.

The interferometric architecture of the FOG has a poor sensitivity at low rates as due to cosine nature of the phase difference and near zero phase at the peak of the cosine function. To achieve better sensitivity, it is necessary to modulate the light which is accomplished in modern FOG configurations through the use of an electro-optic phase modulator. Light passing through the modulator is phase shifted in proportion to the applied voltage. Differential phase shifts between the clockwise and counter-clockwise beams are sustained for only one transit time of the light through the coil and thus the modulation must be applied every transit time.

Phase modulation of the light improves the sensitivity at low angular rates. However, the high rate non-linearity, light intensity variation, photo-detector sensitivity, preamp gain and background intensity all affect the open loop output of the FOG. For this reason, it is important for higher accuracy and greater dynamic range to operate the FOG in a closed loop fashion. The same device that accomplished the phase shifting of the light is typically used to close the loop in the FOG. Because the angular rate sensed by the FOG appears as an interferometer phase shift, it may be nulled out by applying a phase rebalance in additional to the phase shift with the modulator. A complication arises due to the fact that the modulator can produce a differential phase shift between clockwise and counter-clockwise light beams only during the transit time of the light through the fiber coil and a given angular rate produces a persistent phase shift between the light beams. To achieve phase nulling, it is necessary to increase the phase applied at every transit time. A periodic reset is required when the maximum voltage that is supplied to the modulator is reached. The magnitude of this rest must be exactly 2(pi) to avoid introducing a gyro error.

The sensitivity of the FOG is theoretically limited by the photon shot noise which emerges from the statistical distribution of energy of the photon impinging on the photo detector. While the Sagnac sensitivity increases with the length of the fiber, the photon energy decreases with fiber length due to attenuation of the light as it travels through the fiber. Thus a tradeoff must be done when choosing the size of the FOG for a given application. Errors in the FOG output arise through a number of sources. Rayleigh backscattering is the dominant error source in the FOG.

This comes about when backscatter of one beam interferes with the other light beam. Low coherence light sources are used to reduce this effect. Two popular light sources for FOGs are the superluminescent diode (SLD) and the broadband fiber source (BFS). The change in the index of refraction of the fiber as a function of the intensity of the light induces an error through the optical Kerr effect. This effect is also reduced through the use of low coherence light sources. The thermal gradient effect due to uneven heating of the fiber coil is typically the major challenge to achieving required performance in the FOG. The light beam will experience propagation delays due to temperature differences along the length of the fiber. These propagation delays are not the same for the two counter propagating beams which results in a gyro error. Sophisticated coil winding designs, such as quadrupole or octopole can help to minimize this effect. Finally, birefringence effects, from the fiber, can result in errors; good control of the light polarization if required.

The FOG has gained a wide acceptance and is found in a wide variety of applications from undersea to outer space. The performance of the FOG as a gyro is dependent primarily on the diameter of the fiber coil and the length of the fiber. Thus the size of the FOG can vary significantly from coil diameters of approximately an inch with less than 100 meters of fiber to diameters of several inches containing multiple kilometers of fiber depending on the application and performance requirement. The FOG has been shown to have better reliability than that of the RLG and further eliminates the need for any high voltages that are required to initiate and maintain the plasma in the RLG. For these reasons, the marketplace is moving from RLG to FOG. Also, while there are only a few manufacturers of RLG left around the globe, and it is estimated that there may be more than a dozen manufacturers of FOG based systems worldwide.

827. The Hemispherical Resonator Gyro

The Hemispherical Resonator Gyro (HRG) belongs to a class of gyros referred to as Coriolis Vibratory Gyros (CVG). The physics of the HRG is based on the forces arising from the Coriolis Effect which describes the motion of a body undergoing uniform motion in a rotating frame of reference. The HRG was conceived in 1890 when physicist G.H. Bryan struck a wineglass, making an interesting discovery of how the tone from a glass behaved when it was rotated about its stem. To understand the operation of an HRG, consider a thin hemispherical shell, although other suitable configurations can also be used, such as cylindrical, whereas the rim of the shell can be made to vibrate by applying appropriate force and technique. The lowest fundamental mode is characterized by four nodes and four antinodes of vibration. The rim of the shell will then have a radial velocity component at the antinodes and a tangential velocity component at the nodes.

When the shell is subject to an angular rate about its sensitive axis, which is perpendicular to the plane of the standing wave pattern, Coriolis forces are generated. These forces are proportional to the applied angular rate and are orthogonal to both the applied rate vector and the shell's velocity vectors. The result of these forces is standing wave whose nodes and antinodes are now shifted with respect to the original pattern. The superposition of the original wave and the new orthogonal wave result in a phenomenon in which the resultant wave rotates relative to its own casing and to inertial space through an angle that is proportional to the angular rotation of the gyro case. The resultant pattern precesses in the opposite sense. The angular gain factor is a function of the geometrical design and provides a very stable gyro scale factor. The electrical sensing of pattern is typically accomplished through capacitive elements that are implemented between the shell and another element separated from the shell by a suitable gap.

The HRG is attractive as a result of the very low noise figure, one or two order of magnitude better than what can be achieved with either an RLG or FOB of comparable design. Furthermore, due to the simplistic nature of the sending element, the HRG has realized extraordinary reliability with tens of millions of failure-free operations exhibited in space applications. The challenges with the HRG are also related to the simplicity of the sensing element since that results in complexity of the electronics required for operation, HRG electronic functions are broadly grouped into the following categories:

1. Reference phase generation and frequency control
2. Amplitude control
3. Pattern angle readout
4. Quadrature suppression
5. Force-to-rebalance mode of operation
6. Whole angle mode of operation

In the force-to-rebalance mode of operation, the nodes and antinodes are capacitively held in place. The capacitive force required to do this is a measure of the angular rate experienced by the HRG. In this mode of operation, the bias errors can be minimized; however, the gyro scale factor is a function of the electronics and temporal trends in scale factor are observed as the electronics age. The force-to-rebalance mode is limited by the available capacitive forcing. This limits the angular rate range typically to less than 100 deg/sec for practical devices. In the whole angle mode of operation, the pattern is allowed to precess and so the angular rate range is limited only by the processing electronics. As already mentioned, the geometric scale factor is very stable and hence scale factor performance of the HRG is excellent in the whole angle mode; however, the bias performance tends not be as good as in the force-to-rebalance mode.

CORRECTING AND UNCORRECTING THE COMPASS

828. Ship's Heading

Ship's heading is the angle, expressed in degrees clockwise from north, of the ship's fore-and-aft line with respect to the true meridian or the magnetic meridian. When this angle is referred to the true meridian, it is called a **true heading**. When this angle is referred to the magnetic meridian, it is called a **magnetic heading**. Heading, as indicated on a particular compass, is termed the ship's compass heading by that compass. It is essential to specify every heading as true (T), magnetic (M), or compass. Two abbreviations simplify recording of compass directions. The abbreviation PGC refers to "per gyro compass," and PSC refers to "per steering compass." The steering compass is the one being used by the helmsman or autopilot, regardless of type.

829. Variation and Deviation

Variation is the angular measure between the magnetic meridian and the true meridian at a given location. If the northerly part of the magnetic meridian lies to the right of the true meridian, the variation is easterly. Conversely, if this part is to the left of the true meridian, the variation is westerly. The local variation and its small **annual change** are noted on the compass rose of all navigational charts. Thus the true and magnetic headings of a ship differ by the local variation.

As previously explained, a ship's magnetic influence will generally cause the compass needle to deflect from the magnetic meridian. This angle of deflection is called **deviation**. If the north end of the needle points east of the magnetic meridian, the deviation is easterly; if it points west of the magnetic meridian, the deviation is westerly.

830. Heading Relationships

A summary of heading relationships follows:

1. **Deviation** is the difference between the compass heading and the magnetic heading.
2. **Variation** is the difference between the magnetic heading and the true heading.
3. The algebraic sum of deviation and variation is the **compass error**.

The following simple rules will assist in correcting and uncorrecting the compass:

1. Compass least, error east; compass best, error west.
2. When correcting, add easterly errors, subtract westerly errors (Remember: "Correcting Add East").
3. When uncorrecting, subtract easterly errors, add westerly errors.

Some typical correction operations follow:

Compass	Deviation	Magnetic	Variation	True
		-> +E, -W		
358°	5°E	003°	6°E	009°
120°	1°W	119°	3°E	122°
180°	6°E	186°	8°W	178°
240°	5°W	235°	7°W	228°
		+W, -E <-		

Figure 830. Examples of compass correcting.

Use the memory aid "Can Dead Men Vote Twice, At Elections" to remember the conversion process (Compass, Deviation, Magnetic, Variation, True; Add East). When converting compass heading to true heading, add easterly deviations and variations and subtract westerly deviations and variations. "Truly Valiant Marines Don't Cry at Weddings" is another phrase used to remember compass correction where Westerly error is added.

The same rules apply to correcting gyrocompass errors, although gyro errors always apply in the same direction. That is, they are E or W all around the compass.

Complete familiarity with the correcting of compasses is essential for navigation by magnetic or gyro compass. Professional navigators who deals with them continually can do them in their heads quickly and accurately.

CHAPTER 9

DEAD RECKONING

DEFINITION AND PURPOSE

900. Definition and Use

Dead reckoning (DR) is a method for determining the estimated position of a vessel by advancing from a known fix of position along the vessel's ordered course and speed. This can be used to determine where a vessel currently is or where it will be. This is an approximate position; it does not allow for the many errors that can cause a vessel to veer off course such as helmsmen error, compass error, or current and wind.

Dead reckoning helps in predicting landfall, determining distances to objects, predicting arrival times, and evaluating the accuracy of electronic positioning information. It also aids in predicting which celestial bodies will be available for future observation. However, its most important use is in projecting the ship's position in the immediate future and avoiding hazards to navigation.

The navigator should carefully tend his or her DR plot, updating it when required and using it to evaluate external forces acting on his or her ship. Navigators can compare the dead reckoning position to a known fix to determine other forces acting on the vessel, such as wind and current. They can then use all this information to create a more accurate DR plot and stay on course by correcting for the known errors and their effects.

The use of DR when an Electronic Chart Display and Information System (ECDIS) is the primary plotting method can vary with the type of system. An ECDIS can display the ship's heading projected out to show future positions as a function of time, display waypoint information, and/or show progress toward each waypoint in turn.

Presently, marine navigation is in a time of transition with some ships completely paperless and others using a combination of electronic and paper charting. If paper charts are the back up to ECDIS (instead of an additional type-approved ECDIS) it would be prudent to DR as a cross-check to the GPS/GNSS derived position on the ECDIS. Plotting positions on the paper chart should be done at appropriate intervals. The following procedures apply to DR plotting on the traditional paper chart.

CONSTRUCTING THE DEAD RECKONING PLOT

The DR plot should be maintained directly on the chart in use. DR at least two fix intervals ahead while piloting. When transiting on the open ocean, maintain the DR at least four hours ahead of the last fix position. Maintaining the DR plot directly on the chart allows the navigator to evaluate a vessel's future position in relation to charted navigation hazards. It also allows the conning officer and captain to plan course and speed changes required to meet any operational commitments.

This section will discuss how to construct the DR plot.

901. Measuring Courses and Distances

To measure courses, use the chart's compass rose nearest to the chart area currently in use. Transfer course lines to and from the compass rose using parallel rulers, rolling rulers, or triangles. If using a parallel motion plotter (PMP), simply set the plotter at the desired course and plot that course directly on the chart. Transparent plastic navigation plotters that align with the latitude/longitude grid may also be used.

The navigator can measure direction at any convenient place on a Mercator chart. All the meridians are parallel to each other and a line making an angle with any one makes the same angle with all others. When measuring direction on a conformal chart having nonparallel meridians, use the meridian closest to the area of the chart in use. A common nonconformal projection used is the gnomonic; a gnomonic chart usually contains instructions for measuring direction.

Compass roses may give both true and magnetic directions. True directions are on the outside of the rose; magnetic directions are on the inside. For most purposes, use true directions.

Measure distances using the chart's latitude scale. Although not technically true, assuming that one minute of latitude equals one nautical mile introduces no significant error. The latitude scale on a Mercator chart expands as the latitude increases, therefore one must measure distances on the latitude scale closest to the area of interest when working with small-scale charts. On large-scale charts, such as harbor charts, one can use either the latitude scale or the distance scale provided. To measure long distances on small-scale charts, break the distance into a number of segments and measure each segment at its mid-latitude.

902. Plotting and Labeling the Course Line and Positions

Draw a new **course line** whenever restarting the DR. To draw a DR, extend the course line from a fix in the direction of the ordered course. Above the course line place a capital C followed by the ordered course in degrees true. Below the course line, place a capital S followed by the speed in knots. Label all course lines and fixes after plotting them because a conning officer or navigator can easily misinterpret an unlabeled line or position.

Enclose a fix from two or more Lines of Position (LOP) by a small circle and label it with the time to the nearest minute, written horizontally. Mark a DR position with a semicircle and the time, written diagonally. Mark an **estimated position (EP)** by a small square and the time, written horizontally. Determining an EP is covered later in this chapter.

Express the time using four digits without punctuation, using either zone time or Greenwich Mean Time (GMT), according to procedure. Label the plot neatly, succinctly, and clearly.

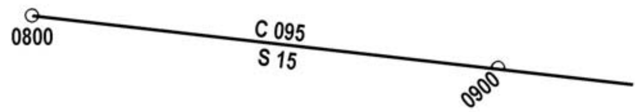


Figure 902. A course line with labels.

Figure 902 illustrates this process. The navigator plots and labels the 0800 fix. The conning officer orders a course of 095°T and a speed of 15 knots. The navigator extends the course line from the 0800 fix in a direction of 095°T. S/He calculates that in one hour at 15 knots he will travel 15 nautical miles. S/He measures 15 nautical miles from the 0800 fix position along the course line and marks that point on the course line with a semicircle. S/He labels this DR with the time. Note that, by convention, he labels the fix time horizontally and the DR time diagonally.

THE FOUR RULES OF DEAD RECKONING

903. Plotting the DR

To effectively maintain the vessel's DR position, the navigator must follow the 4 rules of DR.

Plot a fix:

1. At least every hour on the hour.
2. After every change of course or speed.
3. After every fix or running fix.
4. After plotting a single line of position.

Figure 903 illustrates applying these rules. Clearing the harbor at 0900, the navigator obtains a last visual fix. This is called **taking departure**, and the position determined is called the **departure**. At the 0900 departure, the conning officer orders a course of 090°T and a speed of 10 knots. The navigator lays out the 090°T course line from the departure.

At 1000, the navigator plots a DR position according to the rule requiring plotting a DR position at least every hour on the hour. At 1030, the conning officer orders a course change to 060°T. The navigator plots the 1030 DR position in accordance with the rule requiring plotting a DR position at every course and speed change. Note that the course line changes at 1030 to 060°T to conform to the new course. At 1100, the conning officer changes course back to 090°T. The navigator plots an 1100 DR due to the course change. Note that, regardless of the course change, an 1100 DR would have been required because of the "every hour on the hour" rule.

At 1200, the conning officer changes course to 180°T and speed to 5 knots. The navigator plots the 1200 DR. At 1300, the navigator obtains a fix. Note that the fix position is offset to the east from the DR position. The navigator determines set and drift from this offset and applies this set and drift to any DR position from 1300 until the next fix to determine an estimated position. S/He also resets the DR to the fix; that is, s/he draws the 180°T course line from the 1300 fix, not the 1300 DR.

904. Resetting the DR

Reset the DR plot to each fix or running fix in turn. In addition, consider resetting the DR to an inertial estimated position, if an inertial system is installed.

If a navigator has not taken a fix for an extended period of time, the DR plot, not having been reset to a fix, will accumulate time-dependent errors. Over time that error may become so significant that the DR will no longer show the ship's position with acceptable accuracy. If the vessel is equipped with an inertial navigator, the navigator should consider resetting the DR to the inertial estimated position. Some factors to consider when determining whether to reset the DR are:

(1) Time since the last fix and availability of fix information. If it has been a short time since the last fix and fix information may soon become available, it may be advisable to wait for the next fix to reset the DR.

(2) Dynamics of the navigation situation. If, for example, a submerged submarine is operating in the Gulf Stream, fix information is available but operational considerations may preclude the submarine from going to

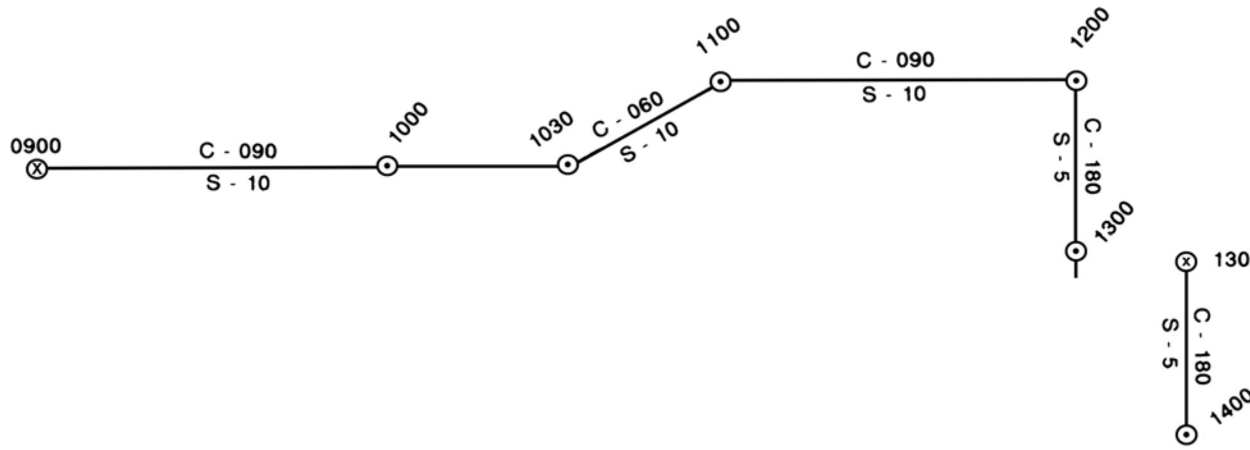


Figure 903. A typical dead reckoning plot.

periscope depth to obtain a fix. Similarly, a surface ship with an inertial navigator may be in a dynamic current and suffer a temporary loss of electronic fix equipment. In either case, the fix information will be available shortly but the dynamics of the situation call for a more accurate assessment of the vessel's position. Plotting an inertial EP and resetting the DR to that EP may provide the navigator with a more accurate assessment of the navigation situation.

(3) Reliability and accuracy of the fix source. If a submarine is operating under the ice, for example, only the inertial EP fixes may be available for weeks at a time. Given a high prior correlation between the inertial EP and highly accurate fix systems such as GPS, and the continued proper operation of the inertial navigator, the navigator may decide to reset the DR to the inertial EP.

DEAD RECKONING AND SHIP SAFETY

Properly maintaining a DR plot is important for ship safety. The DR allows the navigator to examine a future position in relation to a planned track. It allows him to anticipate charted hazards and plan appropriate action to avoid them. Recall that the DR position is only approximate. Using a concept called fix expansion compensates for the DR's inaccuracy and allows the navigator to use the DR more effectively to anticipate and avoid danger.

905. Fix Expansion

Circumstances may arise where a ship steams in the open ocean for extended periods without a fix. This can result from a combination of factors ranging from the inability to obtain celestial fixes to malfunctioning electronic navigation systems. Infrequent fixes are particularly common on submarines. Whatever the reason, in some instances a navigator may find himself in the position of having to steam many hours on DR alone.

Navigators must take precautions to ensure that all hazards to navigation along their path are accounted for by the approximate nature of a DR position. One method which can be used is fix expansion.

Fix expansion takes into account possible errors in the DR calculation caused by factors which tend to affect the vessel's actual course and speed over the ground. The navigator considers all such factors and develops an expanding "error circle" around the DR plot. One of the basic assumptions of fix expansion is that the various individual effects of current, leeway, and **steering error** combine to cause a cumulative error which increases over time, hence, the concept of expansion. While the errors may in fact cancel each other out, the worst case is that they will all be additive, and this is what the navigator must anticipate.

Errors considered in the calculation of fix expansion encompass all errors that can lead to DR inaccuracy. Some of the most important factors are current and wind, compass or gyro error, and steering error. Any method which attempts to determine an error circle must take these factors into account. The navigator can use the magnitude of set and drift calculated from his or her DR plot. See Section 907. The current's estimated magnitude can be obtained from pilot charts or weather reports. Wind speed can be gathered from weather instruments. Compass error can be found by comparison with an accurate standard or by obtaining an azimuth of the Sun. The navigator determines the effect each of these errors has on his of her course and speed over ground, and applies that error to the fix expansion calculation.

As noted previously, error is a function of time; it grows as the ship proceeds along the track without obtaining a fix. Therefore, the navigator must incorporate

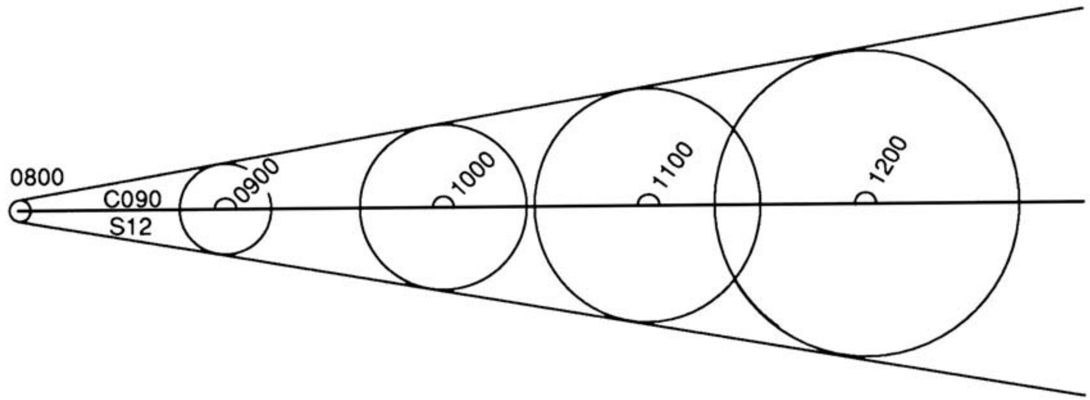


Figure 905. Fix expansion. All possible positions of the ship lie between the lines tangent to the expanding circles. Examine this area for dangers.

the calculated errors into an **error circle** whose radius grows with time. For example, assume the navigator calculates that all the various sources of error can create a cumulative position error of no more than 2 nm. Then his or her fix expansion error circle would grow at that rate; it would be 2 nm after the first hour, 4 nm after the second, and so on.

At what value should the navigator start this error circle? Recall that a DR is laid out from every fix. All fix sources have a finite absolute accuracy, and the initial error circle should reflect that accuracy. Assume, for example, that a satellite navigation system has an accuracy of 0.5 nm. Then the initial error circle around that fix should be set at 0.5 nm.

First, enclose the fix position in a circle, the radius of which is equal to the accuracy of the system used to obtain the fix. Next, lay out the ordered course and speed from the fix position. Then apply the fix expansion circle to the hourly DRs, increasing the radius of the circle by the error factor each time. In the example given above, the DR after one hour would be enclosed by a circle of radius 2.5 nm (that is, 2 nm of cumulative position error + 0.5 nm of satellite navigation error), after two hours 4.5 nm, and so on. Having encircled the four hour DR positions with the error circles, the navigator then draws two lines originating tangent to the original error circle and simultaneously tangent to the other error circles. The navigator then closely examines the area between the two tangent lines for hazards to navigation. This technique is illustrated in Figure 905.

The fix expansion encompasses the total area in which the vessel could be located (as long as all sources of error are considered). If any hazards are indicated within the cone, the navigator should be especially alert for those dangers. If, for example, the fix expansion indicates that the vessel may be standing into shoal water, continuously monitor the fathometer. Similarly, if the fix expansion indicates that the vessel might be approaching a charted obstruction, post extra lookouts.

The fix expansion may grow at such a rate that it becomes unwieldy. Obviously, if the fix expansion grows to cover too large an area, it has lost its usefulness as a tool for the navigator, and he or she should obtain a new fix by any available means.

DETERMINING AN ESTIMATED POSITION

An estimated position (EP) is a DR position corrected for the effects of leeway, steering error, and current. This section will briefly discuss the factors that cause the DR position to diverge from the vessel's actual position. It will then discuss calculating set and drift and applying these values to the DR to obtain an estimated position. It will also discuss determining the estimated course and speed made good.

906. Factors Affecting DR Position Accuracy

Tidal current is the periodic horizontal movement of the sea caused by the tide-affecting gravitational forces of the moon and sun. **Current** is the horizontal movement of the sea caused by meteorological, oceanographic, or topographical effects. From whatever its source, the horizontal motion of the sea is an important dynamic force acting on a vessel.

Set refers to the current's direction, and **drift** refers to the current's speed. **Leeway** is the leeward motion of a vessel due to that component of the wind vector perpendicular to the vessel's track. Leeway and current combine to produce the most pronounced natural dynamic effects on a transiting vessel. Leeway especially affects sailing vessels and high-sided vessels.

In addition to these natural forces, relatively small helmsman and steering compass errors may combine to cause additional error in the DR.

907. Calculating Set and Drift and Plotting an Estimated Position

It is difficult to quantify the errors discussed above individually. However, the navigator can easily quantify their cumulative effect by comparing simultaneous fix and DR positions. If there are no dynamic forces acting on the vessel and no steering error, the DR position and the fix position will coincide. However, this seldom occurs; the fix is normally offset from the DR by the vector sum of all the errors.

Note again that this methodology provides no means to determine the magnitude of the individual errors. It simply provides the navigator with a measurable representation of their combined effect.

When the navigator measures this combined effect, s/he often refers to it as the "set and drift." Recall from above that these terms technically were restricted to describing current effects. However, even though the fix-to-DR offset is caused by effects in addition to the current, this text will follow the convention of referring to the offset as the set and drift.

The set is the direction from the DR to the fix. The drift is the distance in miles between the DR and the fix divided by the number of hours since the DR was last reset. This is true regardless of the number of changes of course or speed since the last fix. The prudent navigator calculates set and drift at every fix.

To calculate an EP, draw a vector from the DR position in the direction of the set, with the length equal to the product of the drift and the number of hours since the last reset. See Figure 907. From the 0900 DR position the navigator draws a set and drift vector. The end of that vector marks the 0900 EP. Note that the EP is enclosed in a square and labeled horizontally with the time. Plot and evaluate an EP with every DR position.

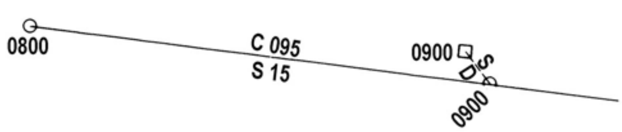


Figure 907. Determining an estimated position.

908. Estimated Course and Speed Made Good

The direction of a straight line from the last fix to the EP is the **estimated track made good**. The length of this line divided by the time between the fix and the EP is the **estimated speed made good**.

Solve for the estimated track and speed by using a vector diagram. See the example problems below and refer to Figure 908a.

Example 1: *A ship on course 080°, speed 10 knots, is steaming through a current having an estimated set of 140° and drift of 2 knots.*

Required: *Estimated track and speed made good.*

Solution: *See Figure 908a. From A, any convenient point, draw AB, the course and speed of the ship, in direction 080°, for a distance of 10 miles.*

From B draw BC, the set and drift of the current, in direction 140°, for a distance of 2 miles.

The direction and length of AC are the estimated track and speed made good.

Answers: *Estimated track made good 089°, estimated speed made good 11.2 knots.*

To find the course to steer at a given speed to make good a desired course, plot the current vector from the origin, A, instead of from B. See Figure 908b.

Example 2: *The captain desires to make good a course of 095° through a current having a set of 170° and a drift of 2.5 knots, using a speed of 12 knots.*

Required: *The course to steer and the speed made good.*

Solution: *See Figure 908b. From A, any convenient point, draw line AB extending in the direction of the course to be made good, 095°.*

From A draw AC, the set and drift of the current.

Using C as a center, swing an arc of radius CD, the speed through the water (12 knots), intersecting line AB at D.

Measure the direction of line CD, 083.5°. This is the course to steer.

Measure the length AD, 12.4 knots. This is the speed made good.

Answers: *Course to steer 083.5°, speed made good 12.4 knots.*

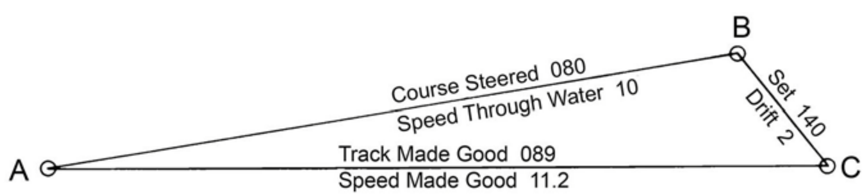


Figure 908a. Finding track and speed made good through a current.

To find the course to steer and the speed to use to make good a desired course and speed, proceed as follows:

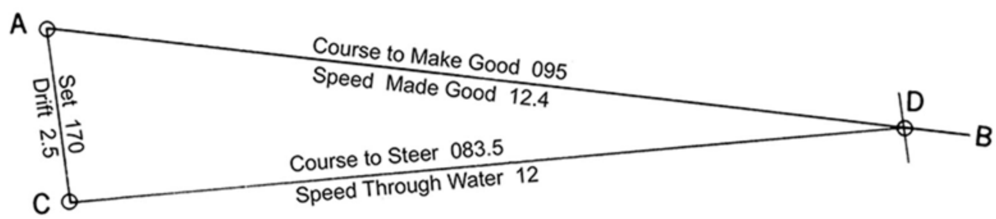


Figure 908b. Finding the course to steer at a given speed to make good a given course through a current.

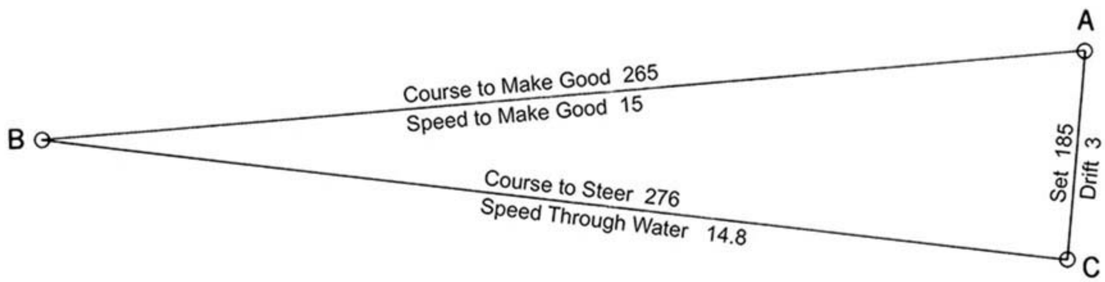


Figure 908c. Finding course to steer and speed to use to make good a given course and speed through the current.

See Figure 908c.

Example 3: *The captain desires to make good a course of 265° and a speed of 15 knots through a current having a set of 185° and a drift of 3 knots.*

Required: *The course to steer and the speed to use.*

Solution: *See Figure 908c. From A, any convenient point, draw AB in the direction of the course to be made good, 265° and for length equal to the speed to be made good, 15 knots.*

From A draw AC, the set and drift of the current.

Draw a straight line from C to B. The direction of this line, 276°, is the required course to steer; and the length, 14.8 knots, is the required speed.

Answers: *Course to steer 276°, speed to use 14.8 knots.*

CHAPTER 10

PILOTING

DEFINITION AND PURPOSE

1000. Introduction

Piloting involves navigating a vessel in restricted waters and fixing its position as precisely as possible at frequent intervals. Proper preparation and attention to detail are more important here than in other phases of navigation. This chapter will discuss a piloting methodology designed to ensure that procedures are carried out safely and efficiently. These procedures will vary from vessel to vessel according to the skills and composition of the piloting team. It is the responsibility of the navigator to choose the procedures applicable to his or her own situation, to train the piloting team in their execution, and to ensure that duties are carried out properly.

These procedures are written primarily from the perspective of the military navigator, with some notes included where civilian procedures might differ. This set of procedures is designed to minimize the chance of error and maximize safety of the ship.

The military navigation team will nearly always consist of several more people than are available to the civilian navigator. Therefore, the civilian navigator must streamline these procedures, eliminating certain steps, doing only what is essential to keep his or her ship in safe water.

The navigation of civilian vessels will therefore proceed differently than for military vessels. For example, while the military navigator might have bearing takers stationed at the gyro repeaters on the bridge wings for taking simultaneous bearings, the civilian navigator must often take and plot them himself. While the military navigator will have a bearing book and someone to record entries for each fix, the civilian navigator will simply plot the bearings on the chart as they are taken and not record them at all.

ECDIS is a good instrument to monitor the vessels track, however, the prudent navigator should continue to actively plot positions. If a pilot is aboard, as is often the case in the most restricted of waters, his or her judgment can generally be relied upon explicitly, further easing the workload. But should the ECDIS fail, the navigator will have to rely on his or her skill in the manual and time-tested procedures discussed in this chapter.

While an ECDIS is the legal equivalent of a paper chart and can be used as the primary plot, an **ECS**, (non-SOLAS compliant electronic chart system) cannot be so used. An ECS may be considered as an additional resource used to ensure safe navigation, but cannot be relied upon for performing all the routine tasks associated with piloting. The individual navigator, with knowledge of his or her vessel, his or her crew, and the capabilities they possess, must make a professional judgment as to how the ECS can support his or her efforts to keep his or her ship in safe water. The navigator should always remember that reliance on any single navigation system courts disaster. An ECS does not relieve the navigator of maintaining a proper and legal plot on a paper chart.

PREPARATION

1001. Plot Setup

The navigator's job begins well before getting underway. Advance preparation is necessary to ensure a safe and efficient voyage. The following steps are representative:

Ensure the plotting station(s) have the following instruments:

- **Dividers:** Dividers are used to measure distances between points on the chart.
- **Compasses:** Compasses are used to plot range arcs for radar LOP's. **Beam compasses** are used when the range arc exceeds the spread of a conventional compass. Both types should be available at the plotting stations.
- **Plotters:** Several types of plotters are available. The preferred device for large vessels is the parallel motion plotter (PMP) used in conjunction with a drafting table. Otherwise, use a transparent protractor plotter, or triangles, parallel rulers or rolling rulers in conjunction with the chart's compass rose. Finally, the plotter can use a one arm protractor. The plotter should use the device with which he or she can work the most quickly and accurately.
- **Sharpened Pencils and Erasers:** Ensure an adequate supply of pencils is available.
- **Nautical Slide Rule:** For solving time, speed, and distance problems.
- **Tide and Current Graphs:** Post the tide and current graphs near the primary plot for easy reference during the transit. Give a copy of the graphs to the conning of-

ficer and the captain.

Once the navigator verifies the above equipment is in place, he or she tapes down the charts on the chart table. If more than one chart is required for the transit, tape the charts in a stack such that the plotter works from the top to the bottom of the stack. This minimizes the time required to shift the chart during the transit. If the plotter is using a PMP, align the arm of the PMP with any meridian of longitude on the chart. While holding the PMP arm stationary, adjust the PMP to read 000.0°T. This procedure calibrates the PMP to the chart in use. Perform this alignment every time the piloting team shifts charts.

Be careful not to fold under any important information when folding the chart on the chart table. Ensure the chart's distance scale, the entire track, and all important warning information are visible.

Energize and test all electronic navigation equipment, if not already in operation. This includes the radar and the GPS receiver. Energize and test the fathometer. Ensure the entire electronic navigation suite is operating properly prior to entering restricted waters.

1002. Preparing Charts and Publications

- **Assemble or Download Required Publications.** These publications should include *Coast Pilots*, *Sailing Directions*, *USCG Light Lists*, *NGA Lists of Lights*, *Tide Tables*, *Tidal Current Tables*, *Notice to Mariners*, and *Local Notice to Mariners*. Often, for military vessels, a port will be under the operational direction of a particular squadron; obtain that squadron's port Operation Order. Civilian vessels should obtain the port's harbor regulations. These publications will cover local regulations such as speed limits and bridge-to-bridge radio frequency monitoring requirements. Assemble and review the Broadcast Notice to Mariners file.
- **Select and Correct Charts.** Choose the largest scale chart available for the harbor approach or departure. Often, the harbor approach will be too long to be represented on only one chart. For example, three charts are required to cover the waters from the Naval Station in Norfolk to the entrance of the Chesapeake Bay. Therefore, obtain all the charts required to cover the entire passage. Using the *Notice to Mariners*, verify that these charts have been corrected through the latest *Notice to Mariners*. Check the *Local Notice to Mariners* and the Broadcast Notice to Mariners file to ensure the chart is fully corrected. Annotate on the chart or a chart correction card all the corrections that have been made; this will make it easier to verify the chart's correction status prior to its next use. Naval ships may need to prepare three sets of charts. One set is for the primary plot, the second set is for the secondary plot, and the third set is for the conning officer and captain. Civilian vessels will prepare one set.
- **Mark the Minimum Depth Contour:** Determine the minimum depth of water in which the vessel can safely operate and outline that depth contour on the chart. Do this step before doing any other harbor navigation planning. Highlight this outline in a bright color so that it clearly stands out. Carefully examine the area inside the contour and mark the isolated shoals less than the minimum depth which fall inside the marked contour. Determine the minimum depth in which the vessel can operate as follows:
- Minimum Depth = Ship's Draft – Height of Tide +
- Safety Margin + Squat. (See Section 1004 and Section 1018.)
- Remember that often the fathometer's transducer is not located at the section of the hull that extends the furthest below the waterline. Therefore, the indicated depth of water is that below the fathometer transducer, not the depth of water below the vessel's deepest draft.
- **Highlight Selected Visual Navigation Aids (NAVAIDS).** Circle, highlight and label the main navigational aids on the chart. Consult the applicable *Coast Pilot* or *Sailing Directions* to determine a port's best NAVAIDS if the piloting team has not visited the port previously. These aids can be lighthouses, piers, shore features, or tanks; any prominent feature that is displayed on the chart can be used as a NAVAID. Label critical buoys, such as those marking a harbor entrance or a traffic separation scheme. Verify charted lights against the *Light List* or the *List of Lights* to confirm the charted information is correct. This becomes most critical when attempting to identify a light at night. Label NAVAIDS succinctly and clearly. Ensure everyone in the navigation team refers to a NAVAID using the same terminology. This will reduce confusion between the bearing taker, the bearing recorder, and plotter.
- **Highlight Selected Radar NAVAIDS.** Highlight radar NAVAIDS with a triangle instead of a circle. If the NAVAID is suitable for either visual or radar piloting, it can be highlighted with either a circle or a triangle.
- **Plot the Departure/Approach Track.** This process is critical for ensuring safe pilotage. Consult the *Fleet Guide* and *Sailing Directions* for recommendations on the best track to use. Look for any information or regulations published by the local harbor authority. Lacking any of this information, locate a channel or safe route on the chart and plot the vessel's track. Most U.S. ports have well-defined channels marked with buoys. Carefully check the intended track to ensure a sufficient depth of water under the keel will exist for the entire passage. If the scale of the chart permits, lay the track out to the starboard side of the channel to allow for any vessel traffic proceeding in the opposite direction. Many channels are marked by natural or

man-made ranges. The bearings of these ranges should be measured to the nearest 0.1° or noted from the *Light List*, and this value should be marked on the chart. Not only are ranges useful in keeping a vessel on track, they are invaluable for determining gyro error. See Section 1007.

- **Label the Departure/Approach Track.** Label the track course to the nearest 0.5°. Similarly, label the distance of each track leg. Highlight the track courses for easy reference while piloting. Often a navigator might plan two separate tracks, for use during good visibility and the other for poor visibility. Considerations might include concern for the number of turns (fewer turns for poor visibility) or proximity to shoal water (smaller margin for error might be acceptable in good visibility). In this case, label both tracks as above and appropriately mark when to use each track.

- **Use Advance and Transfer to Find Turning Points.** The distance the vessel moves along its original course from the time the rudder is put over until the new course is reached is called **advance**. The distance the vessel moves perpendicular to the original course during the turn is called **transfer**. The track determined above does not account for these. See Figure 1002b. Use the advance and transfer characteristics of the vessel to determine when the vessel must put its rudder over to gain the next course. From that point, fair in a curve between the origi-nal course and the new course. Mark the point on the original course where the vessel must put its rudder over as the **turning point**. See Figure 1002c.

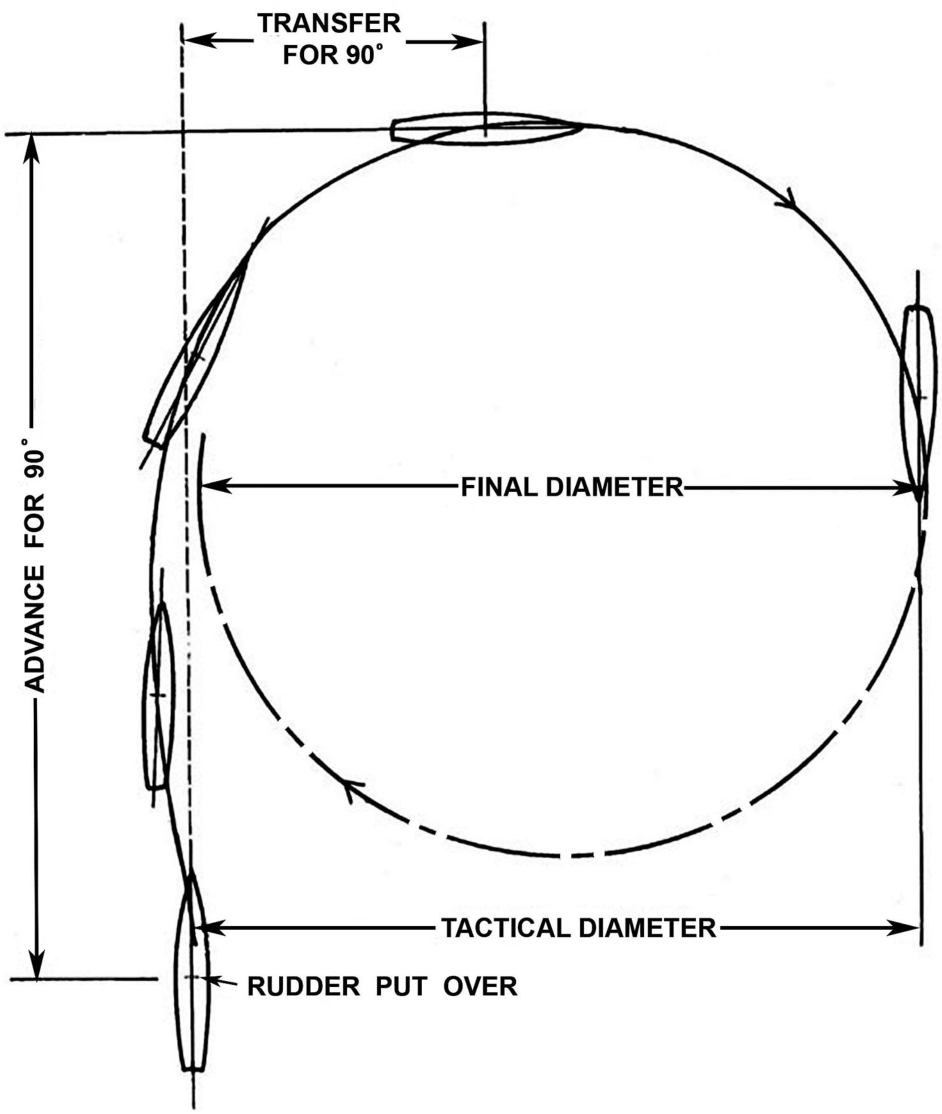


Figure 1002a. Turning circle.

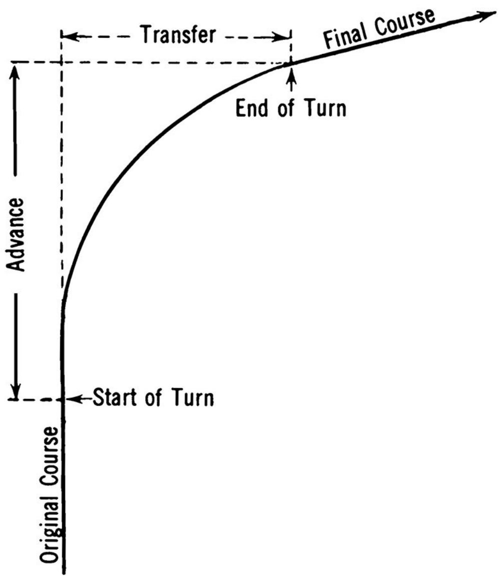


Figure 1002b. Advance and transfer.

- **Plot Turn Bearings and Ranges.** A **turn bearing** is a predetermined bearing to a charted object from the track point at which the rudder must be put over in order to make a desired turn. In selecting a NAVAID for a turn bearing, find one as close to abeam as possible at the turning point, and if possible on the inside elbow of the turn. Account for advance and transfer and label the bearing to the nearest 0.1°. A **turn range** is similar, but taken as a radar range to a prominent object ahead or astern. Ideally, both can be used, one as a check against the other.

Example: *Figure 1002c illustrates using advance and transfer to determine a turn bearing. A ship proceeding on course 100° is to turn 60° to the left to come on a range which will guide it up a channel. For a 60° turn and the amount of rudder used, the advance is 920 yards and the transfer is 350 yards.*

Required: *The bearing of flagpole "FP." when the rudder is put over.*

Solution:

- *Extend the original course line, AB.*
- *At a perpendicular distance of 350 yards, the transfer, draw a line A'B' parallel to the original course line AB. The point of intersection, C, of A'B' with the new course line is the place at which the turn is to be completed.*
- *From C draw a perpendicular, CD, to the original course line, intersecting at D.*
- *From D measure the advance, 920 yards, back along the original course line. This locates E, the point at which the turn should be started.*
- *The direction of "FP." from E, 058°, is the bearing when the turn should be started.*

Answer: *Bearing 058°.*

- **Plot a Slide Bar for Every Turn Bearing:** If the ship is off track immediately prior to a turn, a plotting technique known as the **slide bar** can quickly revise a turn bearing. See Figure 1002d. A slide bar is a line drawn parallel to the new course through the turning point on the original course. The navigator can quickly determine a new turn bearing by dead reckoning ahead from the vessel's last fix position to where the DR intersects the slide bar. The revised turn bearing is simply the bearing from that intersection point to the turn bearing NAVAID. Draw the slide bar with a different color from that used for the track in order to see the slide bar clearly.
- **Label Distance to Go from Each Turn Point:** At each turning point, label the distance to go until either the ship moors (inbound) or the ship clears the harbor (outbound). For an inbound transit, a vessel's captain is usually more concerned about time of arrival, so assume a speed of advance and label each turn point with time to go until mooring.
- **Plot Danger Bearings:** Danger bearings warn a navigator s/he may be approaching a navigational hazard too closely. See Figure 1002e. Vector AB indicates a vessel's intended track. This track passes close to the indicated shoal. Draw a line from the NAVAID H tangent to the shoal. The bearing of that tangent line measured from the ship's track is 074.0°T. In other words, as long as NAVAID H bears *less than* 074°T as the vessel proceeds down its track, the vessel will not ground on the shoal. Hatch the side of the bearing line on the side of the hazard and label the danger bearing NMT (no more than) 074.0°T. For an added margin of safety, the line does not have to be drawn exactly tangent to the shoal. Perhaps, in this case, the navigator might want to set an error margin and draw the danger bearing at 065°T from NAVAID H. Lay down a danger bearing from any appropriate NAVAID in the vicinity of any hazard to navigation. Ensure the track does not cross any danger bearing.
- **Plot Danger Ranges:** The danger range is analogous to the danger bearing. It is a standoff range from an object to prevent the vessel from approaching a hazard too closely.
- **Label Warning and Danger Soundings:** To determine the danger sounding, examine the vessel's proposed track and note the minimum expected sounding. The minimum expected sounding is the difference

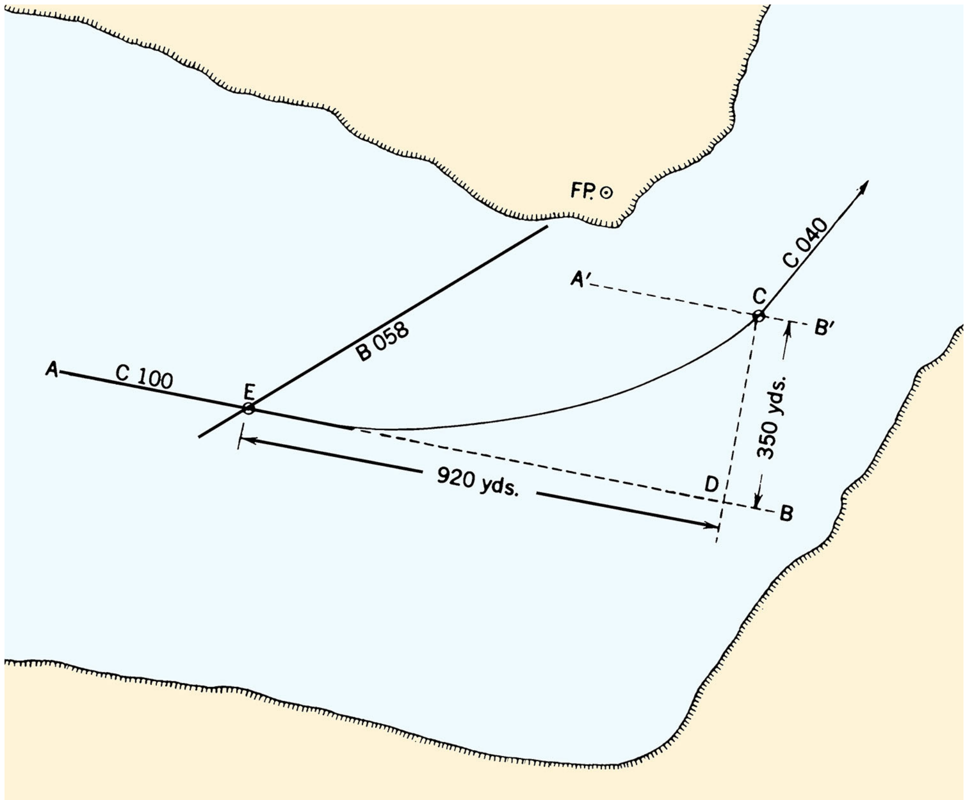


Figure 1002c. Allowing for advance and transfer.

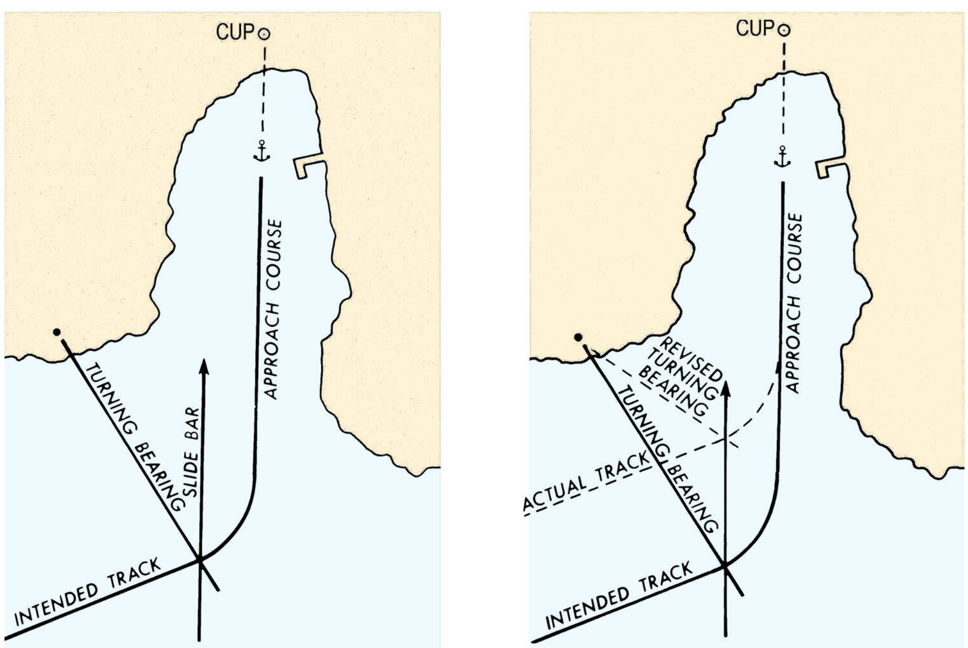


Figure 1002d. The slide bar technique.

between the shallowest water expected on the transit and the vessel's maximum draft. Set 90% of this difference as the warning sounding and 80% of this difference as the danger sounding. The captain may require lower margins. There may be peculiarities about local conditions or forecast wave and swell that will

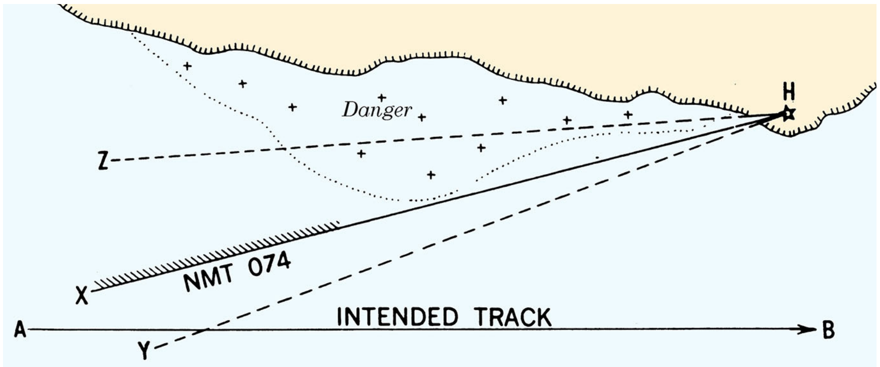


Figure 1002e. A danger bearing, hatched on the dangerous side, labeled with the appropriate bearing.

cause the navigator to choose another method of setting warning and danger soundings. Use the above method if no other means is more suitable. For example: A vessel draws a maximum of 20 feet, and it is entering a channel dredged to a minimum depth of 50 feet. Set the warning and danger soundings at 0.9 (50ft. - 20ft) = 27ft and 0.8 (50ft. - 20ft.) = 24ft., respectively. Re-evaluate these soundings at different intervals along the track, when the minimum expected sounding may change. Carefully label the points along the track between which these warning and danger soundings apply.

- **Label Air Draft:** Label the minimum height for bridges and other height restrictions.
- **Label Demarcation Line:** Clearly label the point on the ship's track where the Inland and International Rules of the Road apply. This is applicable only when piloting in U.S. ports.
- **Mark Speed Limits Where Applicable:** Often a harbor will have a local speed limit in the vicinity of piers, other vessels, or shore facilities. Mark these speed limits and the points between which they are applicable on the chart.
- **Mark the Point of Pilot Embarkation:** Some ports require vessels over a certain size to embark a pilot. If this is the case, mark the point on the chart where the pilot is to embark.
- **Mark the Tugboat Rendezvous Point:** If the vessel requires a tug to moor, mark the tug rendezvous point on the chart.
- **Mark the Chart Shift Point:** If more than one chart will be required to complete the passage, mark the point where the navigator should shift to the next chart.
- **Harbor Communications:** Mark the point on the chart where the vessel must contact harbor control. Also mark the point where a vessel must contact its parent squadron to make an arrival report (military vessels only).
- **Tides and Currents:** Mark the points on the chart for which the tides and currents were calculated.

1003. Records

Ensure the following records are assembled and personnel assigned to maintain them:

- **Bearing Record Book:** The bearing recorders for the primary and secondary plots should record all the bearings used on their plot during the entire transit. The books should clearly list what NAVAIDS are being used and what method of navigation was being used on their plot. In practice, the primary bearing book will contain mostly visual bearings and the secondary bearing book will contain mostly radar ranges and bearings.
- **Fathometer Log:** In restricted waters, monitor soundings continuously and record soundings every five minutes in the fathometer log. Record all fathometer settings that could affect the sounding display.
- **Deck Log:** This log is the legal record of the passage. Record all ordered course and speed changes. Record all the navigator's recommendations and whether the navigator concurs with the actions of the conning officer. Record all buoys passed, and the shift between international and inland Rules of the Road. Record the name and embarkation of any pilot. Record who has the conn at all times. Record any casualty or important event. The deck log combined with the bearing log should constitute a complete record of the passage.

1004. Tides and Currents

Determining the tidal and current conditions of the port is crucial. This process is covered in depth in Chapter 35. In order to anticipate early or late transit, plot a graph of the tidal range for the 24-hour period centered on the scheduled time of arrival or departure. Depending on a vessel's draft and the harbor's depth, some vessels may be able to transit only at high tide. If this is this case, it is critically important to determine the time and range of the tide correctly.

The magnitude and direction of the current will give the navigator some idea of the **set and drift** the vessel will experience during the transit. This will allow him or her to plan in advance for any potential current effects in the vicinity of navigational hazards.

NOAA's National Ocean Services (NOS) ceased printing and distributing annual *Tide Tables* in 1995, however, *Tide Tables* are still printed and distributed under license through several commercial publishers. It is far more efficient to use a computer with appropriate software, or the internet, to compute tides and print out the graphs. These graphs can be posted on the bridge at the chart table for ready reference, and copies made for others involved in the piloting process. The NOAA Tide Prediction service can be accessed through the link provided in Figure 1004. Always remember actual conditions may be quite different from predicted data due to weather or other natural phenomena. In addition the Navigator should be aware of any changes in the draft readings caused by ballasting or the off/onload of material.

Figure 1004. NOAA Tide Prediction Service. https://tidesandcurrents.noaa.gov/tide_predictions.html

1005. Weather

The navigator should obtain a weather report covering the route which s/he intends to transit. This will allow him or her to prepare for any adverse weather by stationing extra lookouts, adjusting speed for poor visibility, and preparing for radar navigation. If the weather is thick, consider standing off the harbor until it clears.

The navigator can receive weather information any number of ways. Military vessels may receive weather reports from their parent squadrons prior to coming into port. Marine band radio carries continuous weather reports. Many vessels are equipped with weather facsimile machines. Some navigators carry cellular phones to reach shoreside personnel and harbor control; these can also be used to get weather reports from NOAA weather stations. If the ship is using a weather routing service for the voyage, it should provide forecasts when asked. Finally, if the vessel has an internet connection, this is an ideal source of weather data. NOAA weather data can be obtained via the link provided in Figure 1005. However s/he obtains the information, the navigator should have a good idea of the weather before entering piloting waters.

Figure 1005. NOAA Weather Data. https://www.ncdc.noaa.gov/data-access/marineocean-data

1006. The Piloting Brief

Assemble the entire navigation team for a piloting brief prior to entering or leaving port. The vessel's captain and navigator should conduct the briefing. All navigation and bridge personnel should attend. The pilot, if s/he is already on board, should also attend. If the pilot is not onboard when the ship's company is briefed, the navigator should immediately brief them when s/he embarks. The pilot must know the ship's maneuvering characteristics before entering restricted waters. The briefing should cover, as a minimum, the following:

- **Detailed Coverage of the Track Plan:** Go over the planned route in detail. Use the prepared and approved chart as part of this brief. Concentrate especially on all the NAVAIDS and soundings which are being used to indicate danger. Cover the buoyage system in use and the port's major NAVAIDS. Point out the radar NAVAIDS for the radar operator. Often, a *Fleet Guide* or *Sailing Directions* will have pictures of a port's NAVAIDS. This is especially important for the piloting party that has never transited a particular port before. If no pictures are available, consider stationing a photographer to take some for submission to NGA.
- **Harbor Communications:** Discuss the bridge-to bridge radio frequencies used to raise harbor control. Discuss what channel the vessel is supposed to monitor on its passage into port and the port's communication protocol.
- **Duties and Responsibilities:** Each member of the piloting team must have a thorough understanding of his or her duties and responsibilities. S/He must also understand how his or her part fits into the whole. The radar plotter, for example, must know if radar will be the primary or secondary source of fix information. The bearing recorder must know what fix interval the navigator is planning to use. Each person must be thoroughly briefed on his or her job; there is little time for questions once the vessel enters the channel.

1007. Evolutions Prior to Piloting

The navigator should always accomplish the following evolutions prior to piloting:

- **Testing the Shaft on the Main Engines in the Astern Direction:** This ensures that the ship can answer a backing bell. If the ship is entering port, no special precautions are required prior to this test. If the ship is tied up at the pier preparing to get underway, exercise extreme caution to ensure no way is placed on the ship while testing the main engines, and the area astern of the vessel is clear of lines or other obstructions.

- **Making the Anchor Ready for Letting Go:** Make the anchor ready for letting go and station a watchstander in direct communications with the bridge at the anchor windlass. Be prepared to drop anchor immediately when piloting if required to keep from drifting too close to a navigational hazard.

- **Calculate Gyro Error:** An error of greater than 1.0° T indicates a gyro problem which should be investigated prior to piloting. There are several ways to determine gyro error:

- Compare the gyro reading with a known accurate heading reference such as an inertial navigator. The difference in the readings is the gyro error.

- Mark the bearing of a charted range as the range NAVAID's come into line and compare the gyro bearing with the charted bearing. The difference is the gyro error.

- Prior to getting underway, plot a dockside fix using at least three lines of position. The three LOP's should intersect at a point. Their intersecting in a "cocked hat" indicates a gyro error. Incrementally adjust each visual bearing by the same amount and direction until the fix plots as a pinpoint. The total correction required to eliminate the cocked hat is the gyro error.

- Measure a celestial body's azimuth or amplitude, or Polaris' azimuth with the gyro, and then compare the measured value with a value computed from the *Sight Reduction Tables* or the *Nautical Almanac*. These methods are covered in detail in Chapter 15.

- Report the magnitude and direction of the gyro error to the navigator and captain. The direction of the error is determined by the relative magnitude of the gyro reading and the value against which it is compared. When the compass is least, the error is east. Conversely, when the compass is best, the error is west. See Chapter 8.

1008. Inbound Voyage Planning

The vessel's planned estimated time of arrival (ETA) at its mooring determines the vessel's course and speed to the harbor entrance. Arriving at the mooring site on time may be important in a busy port which operates its port services on a tight schedule. Therefore, it is important to plan the arrival accurately. Take the desired time of arrival at the mooring and subtract from that the time it will take to navigate to it from the entrance. The resulting time is when you must arrive at the harbor entrance. Next, measure the distance between the vessel's present location and the harbor entrance. Determine the speed of advance (SOA) the vessel will use to make the transit to the harbor. Use the distance to the harbor and the SOA to calculate what time to leave the present position to make the mooring ETA, or what speed must be made good to arrive on time.

Consider these factors which might affect this decision:

- **Weather:** This is the single most important factor in harbor approach planning because it directly affects the vessel's SOA. The thicker the weather, the more slowly the vessel must proceed. Therefore, if heavy fog or rain is in the forecast, the navigator must allow more time for the transit.

- **Mooring Procedures:** Navigators must take more than distance into account when calculating how long it will take them to pilot to their mooring. If the vessel needs a tug, that will increase the time needed. Similarly, picking up or dropping off a pilot adds time to the transit. It is better to allow a margin for error when trying to add up all the time delays caused by these procedures. It is always easier to avoid arriving early by slowing down than it is to make up lost time by speeding up.

- **Shipping Density:** Generally, the higher the shipping density entering and exiting the harbor, the longer it will take to proceed into the harbor entrance safely.

TRANSITION TO PILOTING

1009. Stationing the Piloting Team

At the appropriate time, station the piloting team. Allow plenty of time to acclimate to the navigational situation and if at night, to the darkness. The number and type of personnel available for the piloting team depend on the vessel. A Navy warship, for example, has more people available for piloting than a merchant ship. Therefore, more than one of the jobs listed below may have to be filled by a single person. The piloting team should consist of:

- **The Captain:** The captain is ultimately responsible for the safe navigation of the vessel. His or her judgment regarding navigation is final. The piloting team acts to support the captain, advising him or her so they can make informed decisions on handling the vessel.

- **The Pilot:** The pilot is usually the only member of the piloting team not a member of the ship's company. The piloting team must understand the relationship between the pilot and the captain. The pilot is perhaps the captain's most important navigational advisor. Generally, the captain will follow his or her recommendations when navigating an unfamiliar harbor. The pilot, too, bears some responsibility for the safe passage of the vessel; he or she can be censured for errors of judgment which cause accidents. However, the presence of a pilot in no way relieves the captain of having ultimate responsibility for safe navigation. One exception to this rule is in the Panama Canal per 32 CFR 700.857 where the Commanding Officer is relieved of the responsibility for the safe navigation of the vessel to the canal Pilot. The piloting team works to support and advise the captain.

- **The Officer of the Deck (Conning Officer):** In Navy piloting teams, neither the pilot or the captain usually has the **conn**. The Officer of the Deck (OOD) and the Conning Officer are two different watchstanders. The OOD underway is in charge of the safe operation of the ship and supervises the personnel on watch on the bridge. The Conning Officer directs the ship's movements by rudder and engine orders. The captain can take the conn immediately simply by issuing an order to the helm should an emergency arise. The conning officer of a merchant vessel can be either the pilot, the captain, or another watch officer. In any event, the officer having the conn must be clearly indicated in the ship's deck log at all times. Often a single officer will have the deck and the conn. However, sometimes a junior officer will take the conn for training. In this case, different officers will have the deck and the conn. The officer who retains the deck retains the responsibility for the vessel's safe navigation. US Coast Guard vessels normally split the deck and conn.

- **The Navigator:** The vessel's navigator is the officer directly responsible to the ship's captain for the safe navigation of the ship. S/He is the captain's principal navigational advisor. The piloting team works for the captain. The navigator channels the required information developed by the piloting team to the ship's conning officer on recommended courses, speeds, and turns. The navigator also carefully looks ahead for potential navigational hazards and makes appropriate recommendations. S/He is the most senior officer who devotes his or her effort exclusively to monitoring the navigation picture. The captain and the conning officer are concerned with all aspects of the passage, including contact avoidance and other necessary ship evolutions (making up tugs, maneuvering alongside a small boat for personnel transfers, engineering evolutions, and coordinating with harbor control via radio, for example). The navigator, on the other hand, focuses solely on safe navigation. It is his or her job to anticipate dangers, keep themselves appraised of the navigation situation at all times, and manage the team.

- **Bearing Plotting Team:** This team consists, ideally, of three persons. The first person measures the bearings. The second person records the bearings in an official record book. The third person plots the bearings. The bearing taker should be an experienced individual who has traversed the port before and who is familiar with the NAVAIDS. He or she should take their round of bearings as quickly as possible, beam bearings first, minimizing any time delay errors in the resulting fix. The plotter should also be an experienced individual who can quickly and accurately lay down the required bearings. The bearing recorder can be one of the junior members of the piloting team.

- **The Radar Operator:** The radar operator has one of the more difficult jobs of the team. The radar is as important for collision avoidance as it is for navigation. Therefore, this operator must often "time share" the radar between these two functions. Determining the amount of time spent on these functions falls within the judgment of the captain and the navigator. If the day is clear and the traffic heavy, the captain may want to use the radar mostly for collision avoidance. As the weather worsens, obscuring visual NAVAIDS, the importance of radar for safe navigation increases. The radar operator must be given clear guidance on how the captain and navigator want the radar to be operated.

- **Plot Supervisors:** On many military ships, the piloting team will consist of two plots: the primary plot and the secondary plot. The navigator should designate the type of navigation that will be employed on the primary plot. All other fix sources should be plotted on the secondary plot. The navigator can function as the primary plot supervisor. A senior, experienced individual should be employed as a secondary plot supervisor. The navigator should frequently compare the positions plotted on both plots as a check on the primary plot.

- There are three major reasons for maintaining a primary and secondary plot. First, as mentioned above, the secondary fix sources provide a good check on the accuracy of visual piloting. Large discrepancies between visual and radar positions may point out a problem with the visual fixes that the navigator might not otherwise suspect. Secondly, the navigator often must change the primary means of navigation during the transit. S/He may initially designate visual bearings as the primary fix method only to have a sudden storm or fog obscure the visual NAVAIDS. If s/he shifts the primary fix means to radar, s/he has a track history of the correlation between radar and visual fixes. Finally, the piloting team often must shift charts several times during the transit. When the old chart is taken off the plotting table and before the new chart is secured, there is a period of time when no chart is in use. Maintaining a secondary plot eliminates this complication. Ensure the secondary plot is not shifted prior to getting the new primary plot chart down on the chart table. In this case, there will always be a chart available on which to pilot. Do not consider the primary chart shifted until the new chart is properly secured and the plotter has transferred the last fix from the original chart onto the new chart.

- **Fathometer Operator:** Run the fathometer continuously and station an operator to monitor it. Do not rely on audible alarms to key your attention to this critically important piloting tool. The fathometer operator must know the warning and danger soundings for the area the vessel is transiting. Most fathometers can display either total depth of water or depth under the keel. Set the fathometer to display depth under the keel. The navigator must check the sounding at each fix and compare that value to the charted sounding. A discrepancy between these values is cause for immediate action to take another fix and check the ship's position.

1010. Harbor Approach (Inbound Vessels Only)

The piloting team must make the transition from coastal navigation to piloting smoothly as the vessel approaches restricted waters. There is no rigid demarcation between coastal navigation and piloting. Often visual NAVAIDS are visible miles from shore where GPS is easier to use. The navigator should take advantage of this overlap when approaching the harbor. Plotting GPS, and visual fixes concurrently ensures that the piloting team has correctly identified NAVAIDS and that the different types of systems are in agreement. Once the vessel is close enough to the shore such that sufficient NAVAIDS (at least three with sufficient bearing spread) become visible, the navigator should order visual bearings only for the primary plot and shift all other fixes to the secondary plot, unless the decision has been made to proceed with ECDIS as the primary system.

Take advantage of the coastal navigation and piloting overlap to shorten the fix interval gradually. The navigator must use his of her judgment in adjusting fix intervals. If the ship is steaming inbound directly towards the shore, set a fix interval such that two fix intervals lie between the vessel and the nearest danger. Upon entering restricted waters, the piloting team should be plotting visual fixes at three minute intervals.

Commercial vessels with GPS, planning the harbor transit with a pilot, will approach a coast differently. The transition from ocean to coastal to harbor approach navigation will proceed as visual aids and radar targets appear and are plotted. Once the pilot is aboard, the captain/pilot team may elect to navigate visually, depending on the situation.

TAKING FIXES WHILE PILOTING

Safe navigation while piloting requires frequent fixing of the ship's position whether the vessel is supported by ECDIS or not. If an ECS is in use, it should be considered only a supplement to the paper navigation plot, which legally must still be maintained. As long as the manual plot and the ECS plot are in agreement, the ECS is a valuable tool which shows the navigator where the ship is at any instant, not two or three minutes ago when the last fix was taken. It cannot legally take the place of the paper chart and the manual plot, but it can provide an additional measure of assurance that the ship is in safe water and alert the navigator to a developing dangerous situation before the next round of bearings or ranges.

The next several articles will discuss the three major manual methods used to fix a ship's position when piloting: crossing lines of position, copying satellite data, or advancing a single line of position. Using one method does not exclude using other methods. The navigator must obtain as much information as possible and employ as many of these methods as necessary.

1011. Types of Fixes

While the intersection of two LOP's constitutes a **fix** under one definition, and only an estimated position by another, the prudent navigator will always use at least three LOP's if they are available, so that an error is apparent if they don't meet in a point. Some of the most commonly used methods of obtaining LOP's are discussed below:

- **Fix by Bearings:** The navigator can take and plot bearings from two or more charted objects. This is the most common and often the most accurate way to fix a vessel's position. Bearings may be taken directly to charted objects, or tangents of points of land. See Figure 1011a. The intersection of these lines constitutes a fix. A position taken by bearings to buoys should not be considered a fix, but an estimated position (EP), because buoys swing about their watch circle and may be out of position.

- **Fix by Ranges:** The navigator can plot a fix consisting of the intersection of two or more range arcs from charted objects. S/He can obtain an object's range in several ways:

- **1. Radar Ranges:** See Figure 1011b. The navigator may take ranges to two fixed objects. The intersection of the range arcs constitutes a fix. S/He can plot ranges from any point on the radar scope which s/he can correlate on his or her chart. Remember that the shoreline of low-lying land may move many yards in an area of large tidal range, and swampy areas may be indistinct.

- **2. Stadimeter Ranges:** Given a known height of a NAVAID, one can use a stadimeter to determine its

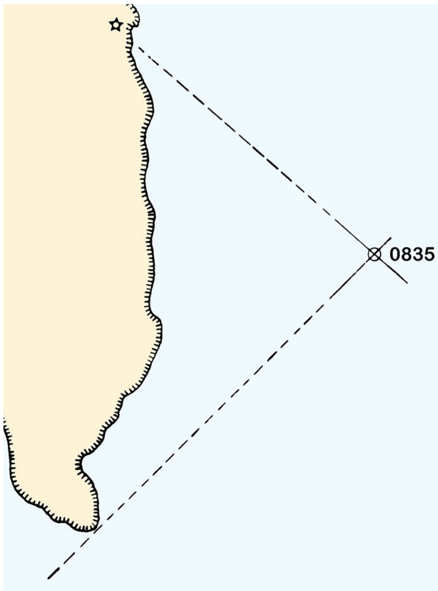


Figure 1011a. A fix by two bearing lines.

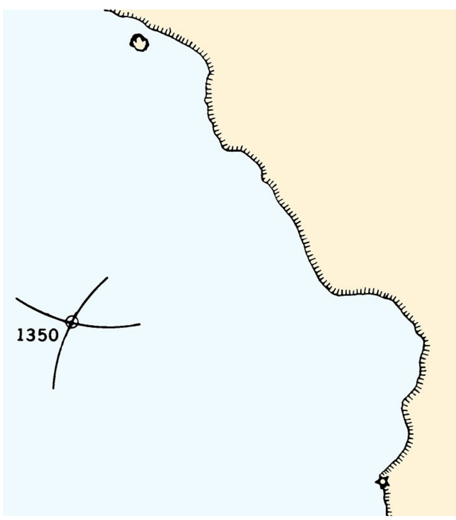


Figure 1011b. A fix by two radar ranges.

range. See Figure 1011c for a representation of the geometry involved. Generally, stadimeters contain a height scale on which is set the height of the object. The observer then directs his or her line of sight through the stadimeter to the base of the object being observed. Finally, s/he adjusts the stadimeter's range index until the object's top reflection is "brought down" to the visible horizon. Read the object's range off the range index.

- **3. Sextant Vertical Angles:** Measure the vertical angle from the top of the NAVAID to the waterline below the NAVAID. Enter Table 16 to determine the distance of the NAVAID. The navigator must know the height of the NAVAID above sea level to use this table; it can be found in the *Light List*.
- **4. Sonar Ranges:** If the vessel is equipped with a sonar suite, the navigator can use sonar echoes to determine ranges to charted underwater objects. It may take some trial and error to set the active signal strength at a value that will give a strong return and still not cause excessive reverberation. Check local harbor restrictions on energizing active sonar. Avoid active sonar transmissions in the vicinity of divers.
- **Fix by Bearing and Range:** This is a hybrid fix of LOP's from a bearing and range to a single object. The radar is the only instrument that can give simultaneous range and bearing information to the same object. (A sonar system can also provide bearing and range information, but sonar bearings are far too inaccurate to use in piloting.) Therefore, with the radar, the navigator can obtain an instantaneous fix from only one NAVAID. This unique fix is shown in Figure 1011d. This makes the radar an extremely useful tool for the piloting team. The radar's characteristics make it much more accurate determining range than determining bearing; therefore, two radar ranges are preferable to a radar range and bearing.
- **Electronic Range Finder:** A modern electronic range finder may be used for the same purpose as a stadimeter. The Coast Guard uses electronic range finders to augment the **stadimeter** during underway replenishment and other station keeping operations when vessels are too close for accurate radar ranging.
- **Fix by Range Line and Distance:** When the vessel comes in line with a range, plot the bearing to the range (while checking compass error in the bargain) and cross this LOP with a distance from another NAVAID. Figure 1011e shows this fix.

1012. The Running Fix

When only one NAVAID is available from which to obtain bearings, use a technique known as the **running fix**. Use the following method:

- Plot a bearing to a NAVAID (LOP 1).
- Plot a second bearing to a NAVAID (either the same NAVAID or a different one) at a later time (LOP 2).
- Advance LOP 1 to the time when LOP 2 was taken.
- The intersection of LOP 2 and the advanced LOP 1 constitute the running fix.

Figure 1012a represents a ship proceeding on course 020°, speed 25 knots. At 1505, the plotter plots an LOP to a lighthouse bearing 310°. The ship can be at any point on this 1505 LOP. Some possible points are represented as points A, B, C, D, and E in Figure 1012a. Six minutes later the ship will have traveled 2.5 miles in direction 020°. If the

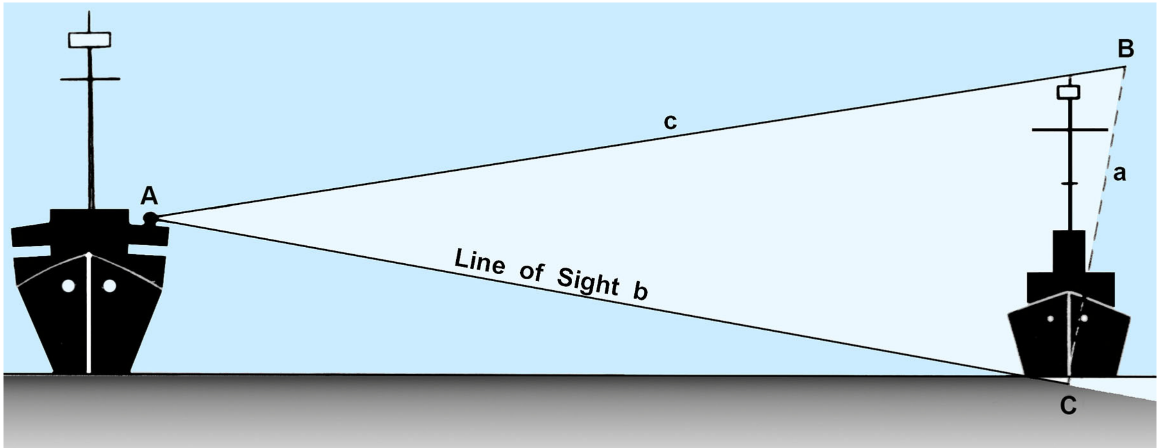


Figure 1011c. Principle of stadimeter operation.

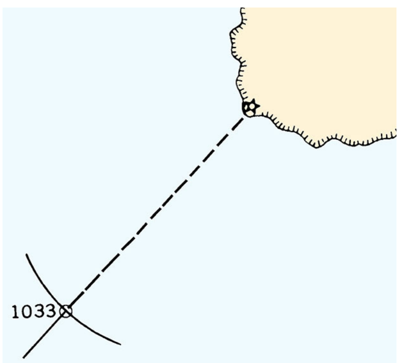


Figure 1011d. A fix by range and bearing of a single object.

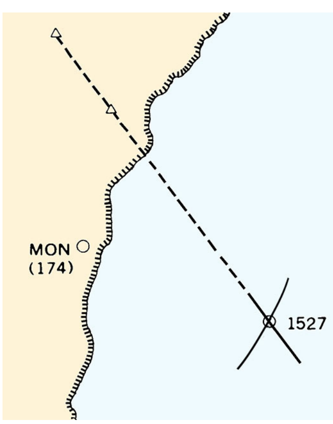


Figure 1011e. A fix by a range and distance.

ship was at A at 1505, it will be at A' at 1511. However, if the position at 1505 was B, the position at 1511 will be B'. A similar relationship exists between C and C', D and D', E and E'. Thus, if any point on the original LOP is moved a distance equal to the distance run in the direction of the motion, a line through this point parallel to the original line of position

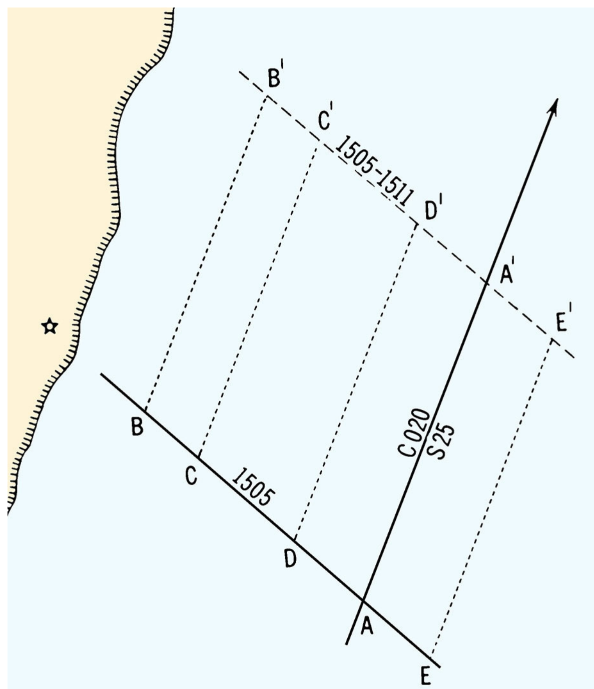


Figure 1012a. Advancing a line of position.

represents all possible positions of the ship at the later time. This process is called **advancing** a line of position. Moving a line back to an earlier time is called **retiring** a line of position.

When advancing a line of position, account for course changes, speed changes, and set and drift between the two bearing lines. Three methods of advancing an LOP are discussed below:

Method 1: See Figure 1012b. To advance the 1924 LOP to 1942, first apply the best estimate of set and drift to the 1942 DR position and label the resulting position point B. Then, measure the distance between the dead reckoning position at 1924 (point A) and point B. Advance the LOP a distance equal to the distance between points A and B. Note that LOP A'B' is

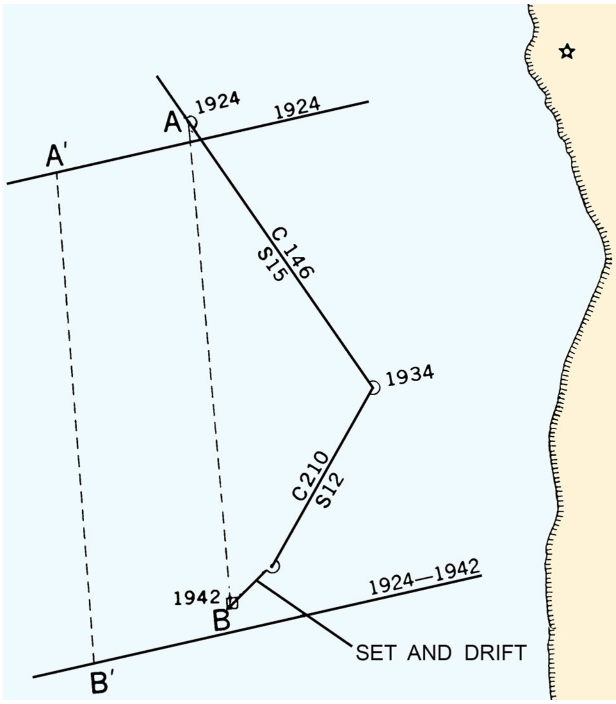


Figure 1012b. Advancing a line of position with a change in course and speed, allowing for set and drift.

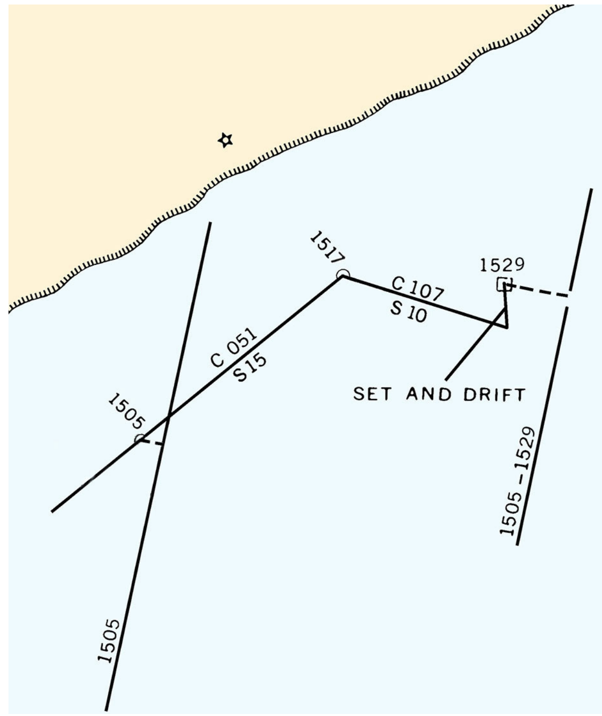


Figure 1012d. Advancing a line of position by its relation to the dead reckoning.

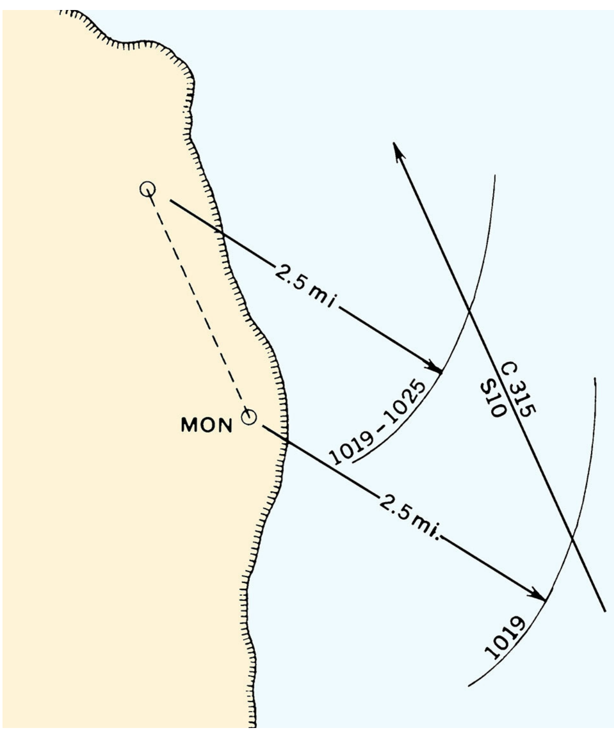


Figure 1012c. Advancing a circle of position.

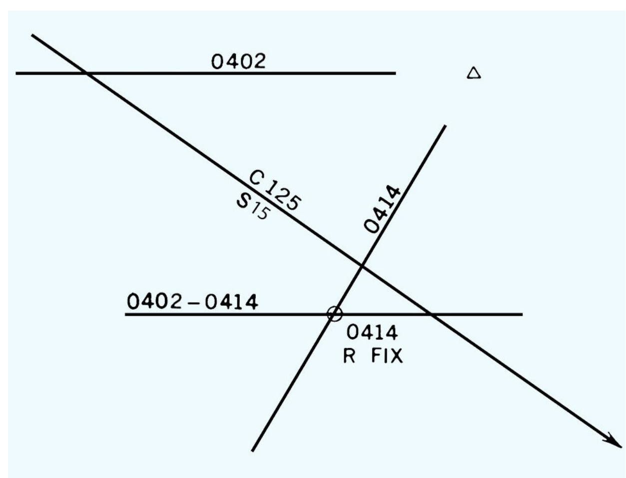


Figure 1012e. A running fix by two bearings on the same object.

in the same direction as line AB.

Method 2: See Figure 1012c. Advance the NAVAIDS position on the chart for the course and distance traveled by the vessel and draw the line of position from the NAVAIDS advanced position. This is the most satisfactory method for advancing a circle of position.

Method 3: See Figure 1012d. To advance the 1505 LOP to 1529, first draw a correction line from the 1505 DR position to the 1505 LOP. Next, apply a set and drift correction to the 1529 DR position. This results in a 1529 estimated position (EP). Then, draw from the 1529 EP a correction line of the same length and direction as the one

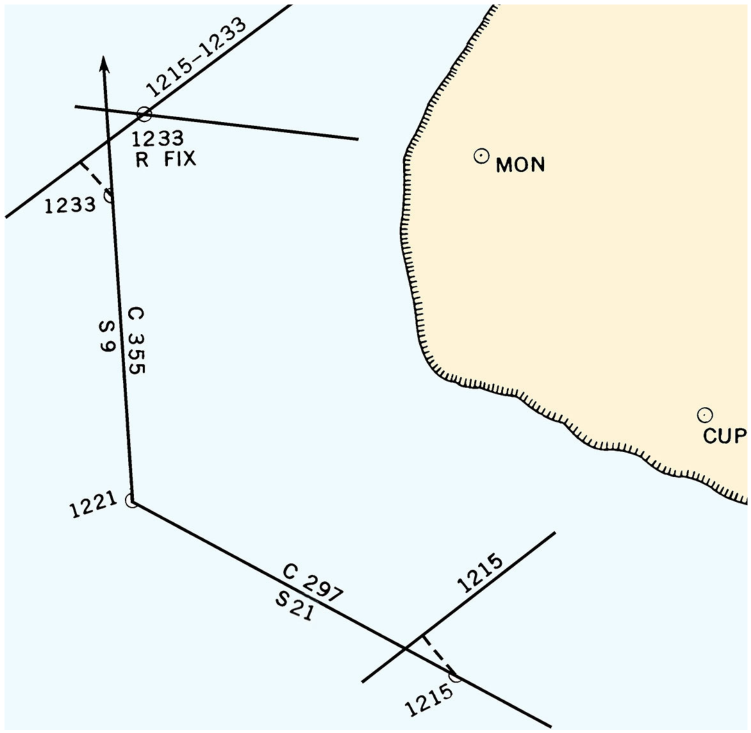


Figure 1012f. A running fix with a change of course and speed between observations on separate landmarks.

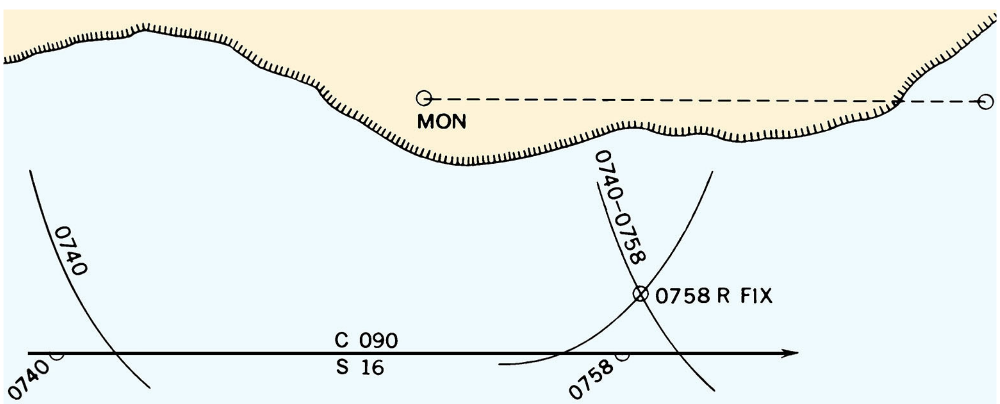


Figure 1012g. A running fix by two circles of position.

drawn from the 1505 DR to the 1505 LOP. Finally, parallel the 1505 bearing to the end of the correction line as shown.

Label an advanced line of position with both the time of observation and the time to which the line is adjusted.

Figure 1012e through Figure 1012g demonstrate three running fixes. Figure 1012e illustrates the case of obtaining a running fix with no change in course or speed between taking two bearings on the same NAVAID. Figure 1012f illustrates a running fix with changes in a vessel's course and speed between taking two bearings on two different objects. Finally, Figure 1012g illustrates a running fix obtained by advancing range circles of position using the second method discussed above.

PILOTING PROCEDURES

The previous section discussed the methods for fixing the ship's position. This section discusses integrating the manual fix methods discussed above, and the use of the fathometer, into a piloting procedure. The navigator must develop his or her piloting procedure to meet several requirements. He or she must obtain enough information to fix the position of the vessel without question. He or she must also plot and evaluate this information. Finally, s/he must relay his or her evaluation and recommendation to the vessel's conning officer. This section examines some considerations to ensure the navigator accomplishes all these requirements quickly and effectively. Of course, if ECDIS is the primary plot, manual methods as discussed here are for backup use.

1013. Fix Type and Fix Interval

The preferred piloting fix is taken from visual bearings from charted fixed NAVAIDS. Plot visual bearings on the primary plot and plot all other fixes on the secondary plot. If poor visibility obscures visual NAVAIDS, shift to radar piloting on the primary plot. If neither visual nor radar piloting is available, consider standing off until the visibility improves.

The interval between fixes in restricted waters should usually not exceed three minutes. Setting the fix interval at three minutes optimizes the navigator's ability to assimilate and evaluate all available information. S/He must relate it to charted navigational hazards and to his or her vessel's intended track. It should take a well trained plotting team no more than 30 seconds to measure, record, and plot three bearings to three separate NAVAIDS. The navigator should spend the majority of the fix interval time interpreting the information, evaluating the navigational situation, and making recommendations to the conning officer.

If three minutes goes by without a fix, inform the captain and try to plot a fix as soon as possible. If the delay was caused by a loss of visibility, shift to radar piloting. If the delay was caused by plotting error, take another fix. If the navigator cannot get a fix down on the plot for several more minutes, consider slowing or stopping the ship until its position can be fixed. Never continue a passage through restricted waters if the vessel's position is uncertain.

The secondary plot supervisor should maintain the same fix interval as the primary plot. Usually, this means s/he should plot a radar fix every three minutes. S/He should plot other fix sources (GPS fixes, for example) at an interval sufficient for making meaningful comparisons between fix sources. Every third fix interval, s/he should pass a radar fix to the primary plot for comparison with the visual fix. S/He should inform the navigator how well all the fix sources plotted on the secondary plot are tracking.

1014. The Piloting Routine

Following a cyclic routine ensures the timely and efficient processing of data and forms a smoothly functioning piloting team. It quickly gives the information which the navigator needs to make informed recommendations to the conning officer and captain.

Repeat this routine at each fix interval beginning when the ship gets underway until it clears the harbor (outbound) or when the ship enters the harbor until it is moored (inbound).

The routine consists of the following steps:

- Take, plot and label a fix.
- Calculate set and drift from the DR position.
- Reset the DR from the fix and DR two fixes ahead.
- **Plotting the Fix:** This involves coordination between the navigator, bearing taker(s), recorder, and plotter. The navigator will call for each fix at the DR time. The bearing taker must measure his or her bearings as quickly as possible, beam bearings first, fore and aft last, on the navigator's mark. The recorder will write the bearings in the book, and the plotter will plot them immediately.
- **Labeling the Fix:** The plotter should clearly mark a visual fix with a circle or an electronic fix with a triangle. Clearly label the time of each fix. A visual running fix should be circled, marked "R Fix" and labeled with the time of the second LOP. Keep the chart neat and uncluttered when labeling fixes.
- **Dead Reckoning Two Fix Intervals Ahead:** After labeling the fix, the plotter should dead reckon the fix position ahead two fix intervals. The navigator should carefully check the area marked by this DR for any navigational hazards. If the ship is approaching a turn, update the turn bearing as discussed in Section 1002.
- **Calculate Set and Drift at Every Fix:** Calculating set and drift is covered in Chapter 9. Calculate these values at every fix and inform the captain and conning officer. Compare the actual values of set and drift with the predicted values from the current graph discussed in Section 1004. Evaluate how the current is affecting the vessel's position in relation to the track and recommend courses and speeds to regain the planned track. Because the navigator can determine set and drift only when comparing fixes and DR's plotted for the same time, take fixes exactly at the times for which a DR has been plotted. Repeat this routine at each fix interval beginning when the ship gets underway until it clears the harbor (outbound) or when the ship enters the harbor until she is moored (inbound).
- **Piloting Routine When Turning:** Modify the cyclic routine slightly when approaching a turn. Adjust the fix interval so that the plotting team has a fix plotted approximately one minute before a scheduled turn. This gives the navigator sufficient time to evaluate the position in relation to the planned track, DR ahead to the slide bar to determine a new turn bearing, relay the new turn bearing to the conning officer, and then monitor the turn bearing to mark the turn.

Approximately 30 seconds before the time to turn, train the alidade on the turn bearing NAVAID. Watch the bearing of the NAVAID approach the turn bearing. About 1° away from the turn bearing, announce to the conning officer: "Stand by to turn." Slightly before the turn bearing is indicated, report to the conning officer: "Mark the turn." Make this report slightly before the bearing is reached because it takes the conning officer a finite amount of time to acknowledge the report and order the helmsman to put over the rudder. Additionally, it takes a finite amount of time for the helmsman to turn the rudder and for the ship to start to turn. If the navigator waits until the turn bearing is indicated to report the turn, the ship will turn too late.

Once the ship is steady on the new course, immediately take another fix to evaluate the vessel's position in relation to the track. If the ship is not on the track after the turn, calculate and recommend a course to the conning officer to regain the track.

1015. Using the Fathometer

Use the fathometer to determine whether the depth of water under the keel is sufficient to prevent the ship from grounding and to check the actual water depth with the charted water depth at the fix position. The navigator must compare the charted sounding at every fix position with the fathometer reading and report to the captain any discrepancies. Taking continuous soundings in restricted waters is mandatory.

See the discussion of calculating the warning and danger soundings in Section 1002. If the warning sounding is received, then slow the ship, fix the ship's position more frequently, and proceed with extreme caution. Ascertain immediately where the ship is in the channel; if the minimum expected sounding was noted correctly, the warning sounding indicates the vessel may be leaving the channel and standing into shoal water. Notify the vessel's captain and conning officer immediately.

If the danger sounding is received, take immediate action to get the vessel back to deep water. Reverse the engines and stop the vessel's forward movement. Turn in the direction of the deepest water before the vessel loses steerageway. Consider dropping the anchor to prevent the ship from drifting aground. The danger sounding indicates that the ship has left the channel and is standing into immediate danger. It requires immediate corrective action by the ship's conning officer, navigator, and captain to avoid disaster.

Many underwater features are poorly surveyed. If a fathometer trace of a distinct underwater feature can be obtained along with accurate position information, send the fathometer trace and related navigational data to NGA for entry into the Digital Bathymetric Data Base.

PILOTING TO AN ANCHORAGE

1016. Choosing an Anchorage

Most U.S. Navy vessels receive instructions in their movement orders regarding the choice of anchorage. Merchant ships are often directed to specific anchorages by harbor authorities. However, lacking specific guidance, the mariner should choose his or her anchoring positions using the following criteria:

- **Depth of Water:** Choose an area that will provide sufficient depth of water through an entire range of tides. Water too shallow will cause the ship to go aground, and water too deep will allow the anchor to drag.
- **Type of Bottom:** Choose the bottom that will best hold the anchor. Avoid rocky bottoms and select sandy or muddy bottoms if they are available.
- **Proximity to navigational Hazards:** Choose an anchorage as far away as possible from known navigational hazards.
- **Proximity to Adjacent Ships:** Anchor well away from adjacent vessels; ensure that another vessel will not swing over your own anchor on a current or wind shift.
- **Proximity to Harbor Traffic Lanes:** Anchor clear of traffic lanes and ensure that the vessel will not swing into the channel on a current or wind shift.
- **Weather:** Choose an area with the weakest winds and currents.
- **Availability of NAVAIDS:** Choose an anchorage with several NAVAIDS available for monitoring the ship's position when anchored.

1017. Navigational Preparations for Anchoring

It is usually best to follow an established procedure to ensure an accurate positioning of the anchor, even when anchoring in an open roadstead. The following procedure is representative. See Figure 1017.

Locate the selected anchoring position on the chart. Consider limitations of land, current, shoals, and other vessels when determining the direction of approach. Where conditions permit, make the approach heading into the current. Close observation of any other anchored vessels will provide clues as to which way the ship will lie to her anchor. If wind and current are strong and from different directions, ships will lie to their anchors according to the balance between these two forces and the draft and trim of each ship. Different ships may lie at different headings in the same anchorage depending on the balance of forces affecting them.

Approach from a direction with a prominent NAVAID, preferably a range, available dead ahead to serve as a steering guide. If practicable, use a straight approach of at least 1200 yards to permit the vessel to steady on the required course. Draw in the approach track, allowing for advance

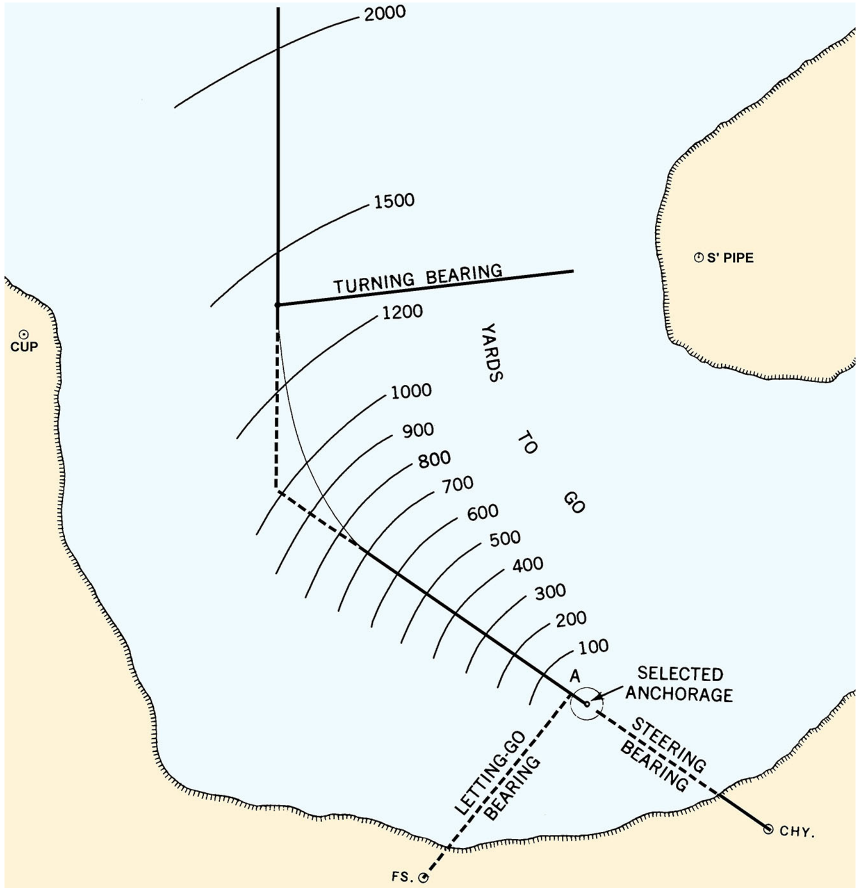


Figure 1017. Anchoring.

and transfer during any turns. In Figure 1017, the chimney was selected as this steering bearing. A turn range may also be used if a radar-prominent object can be found directly ahead or astern.

Next, draw a circle with the selected position of the anchor as the center, and with a radius equal to the distance between the hawsepipe and pelorus, alidade, or periscope used for measuring bearings. This circle is marked "A" in Figure 1017. The intersection of this circle and the approach track is the position of the vessel's bearing-measuring instrument at the moment of letting the anchor go. Select a NAVAID which will be on the beam when the vessel is at the point of letting go the anchor. This NAVAID is marked "FS" in Figure 1017. Determine what the bearing to that object will be when the ship is at the drop point and measure this bearing to the nearest 0.1°T. Label this bearing as the letting go bearing.

During the approach to the anchorage, plot fixes at frequent intervals. The navigator must advise the conning officer of any tendency of the vessel to drift from the desired track. The navigator must frequently report to the conning officer the distance to go, permitting adjustment of the speed so that the vessel will be dead in the water or have very slight sternway when the anchor is let go. To aid in determining the distance to the drop point, draw and label a number of range arcs as shown in Figure 1017 representing distances to go to the drop point.

At the moment of letting the anchor go, take a fix and plot the vessel's exact position on the chart. This is important in the construction of the swing and drag circles discussed below. To draw these circles accurately, determine the position of the vessel at the time of letting go the anchor as accurately as possible.

Veer the anchor chain to a length equal to five to seven times the depth of water at the anchorage. The exact amount to veer is a function of both vessel type and severity of weather expected at the anchorage. When calculating the scope of anchor chain to veer, take into account the maximum height of tide.

Once the ship is anchored, construct two separate circles around the ship's position when the anchor was dropped. These circles are called the **swing circle** and the **drag circle**. Use the swing circle to check for navigational hazards and use the drag circle to ensure the anchor is holding.

The swing circle's radius is equal to the sum of the ship's length and the scope of the anchor chain released. This represents the maximum arc through which a ship can swing while riding at anchor if the anchor holds. Examine this swing circle carefully for navigational hazards, interfering contacts, and other anchored shipping. Use the lowest height of tide expected during the anchoring period when checking inside the swing circle for shoal water.

The drag circle's radius equals the sum of the hawsepipe to pelorus distance and the scope of the chain released. Any bearing taken to check on the position of the ship should, if the anchor is holding, fall within the drag circle. If a fix falls outside of that circle, then the anchor is dragging. If the vessel has a GPS or system with an off-station alarm, set the alarm at the drag circle radius, or slightly more.

In some cases, the difference between the radii of the swing and drag circles will be so small that, for a given chart scale, there will be no difference between the circles when plotted. If that is the case, plot only the swing circle and treat that circle as both a swing and a drag circle. On the other hand, if there is an appreciable difference in radii between the circles when plotted, plot both on the chart. Which method to use falls within the sound judgment of the navigator.

When determining if the anchor is holding or dragging, the most crucial period is immediately after anchoring. Fixes should be taken frequently, at least every three minutes, for the first thirty minutes after anchoring. The navigator should carefully evaluate each fix to determine if the anchor is holding. If the anchor is holding, the navigator can then increase the fix interval. What interval to set falls within the judgment of the navigator, but the interval should not exceed 30 minutes. If an ECDIS or GPS is available, use its off-station alarm feature for an additional safety factor.

NAVIGATIONAL ASPECTS OF SHIP HANDLING

1018. Effects Of Banks, Channels, and Shallow Water

A ship moving through shallow water experiences pronounced effects from the proximity of the nearby bottom. Similarly, a ship in a channel will be affected by the proximity of the sides of the channel. These effects can easily cause errors in piloting which lead to grounding. The effects are known as **squat**, **bank cushion**, and **bank suction**. They are more fully explained in texts on shiphandling, but certain navigational aspects are discussed below.

Squat is caused by the interaction of the hull of the ship, the bottom, and the water between. As a ship moves through shallow water, some of the water it displaces rushes under the vessel to rise again at the stern. This causes a venturi effect, decreasing upward pressure on the hull. Squat makes the ship sink deeper in the water than normal and slows the vessel. The faster the ship moves through shallow water, the greater is this effect; groundings on both charted and uncharted shoals and rocks have occurred because of this phenomenon, when at reduced speed the ship could have safely cleared the dangers. When navigating in shallow water, the navigator must reduce speed to avoid squat. If bow and stern waves nearly perpendicular the direction of travel are noticed, and the vessel slows with no change in shaft speed, squat is occurring. Immediately slow the ship to counter it. Squatting occurs in deep water also, but is more pronounced and dangerous in shoal water. The large waves generated by a squatting ship also endanger shore facilities and other craft.

Bank cushion is the effect on a ship approaching a steep underwater bank at an oblique angle. As water is forced into the narrowing gap between the ship's bow and the shore, it tends to rise or pile up on the landward side, causing the ship to sheer away from the bank.

Bank suction occurs at the stern of a ship in a narrow channel. Water rushing past the ship on the landward side exerts less force than water on the opposite or open water side. This effect can actually be seen as a difference in draft readings from one side of the vessel to the other, and is similar to the venturi effect seen in squat. The stern of the ship is forced toward the bank. If the ship gets too close to the bank, it can be forced sideways into it. The same effect occurs between two vessels passing close to each other.

These effects increase as speed increases. Therefore, in shallow water and narrow channels, navigators should decrease speed to minimize these effects. Skilled pilots may use these effects to advantage in particular situations, but the average mariner's best choice is slow speed and careful attention to piloting.

ADVANCED PILOTING TECHNIQUES

1019. Assuming Current Values to Set Safety Margins for Running Fixes

Current affects the accuracy of a running fix. Consider, for example, the situation of an unknown head current. In Figure 1019a, a ship is proceeding along a coast, on course 250 ° speed 12 knots. At 0920 light A bears 190°, and at 0930 it bears 143°. If the earlier bearing line is advanced a distance of 2 miles (10 minutes at 12 knots) in the direction of the course, the running fix is as shown by the solid lines. However, if there is a head current of 2 knots, the ship is making good a speed of only 10 knots, and in 10 minutes will travel a distance of only 1 $^{2}/_{3}$ miles. If the first bearing line is advanced this distance, as shown by the broken line, the actual position of the ship is at B. This actual position is nearer the shore than the running fix actually plotted. A following current, conversely, would show a position too far from the shore from which the bearing was measured.

If the navigator assumes a following current when advancing his or her LOP, the resulting running fix will plot further from the NAVAID than the vessel's actual position. Conversely, if s/he assumes a head current, the running fix will plot closer to the NAVAID than the vessel's actual position. To ensure a margin of safety when plotting running fix bearings to a NAVAID on shore, always assume the current slows a vessel's speed over ground. This will cause the running fix to plot closer to the shore than the ship's actual position.

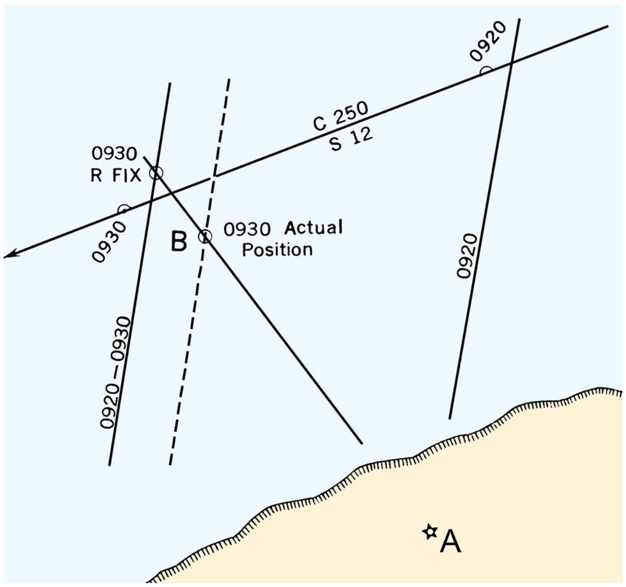


Figure 1019a. Effect of a head current on a running fix.

When taking the second running fix bearing from a different object, maximize the speed estimate if the second object is on the same side and farther forward, or on the opposite side and farther aft, than the first object was when observed.

All of these situations assume that danger is on the same side as the object observed first. If there is either a head or following current, a series of running fixes based upon a number of bearings of the same object will plot in a straight line parallel to the course line, as shown in Figure 1019b. The plotted line will be too close to the object observed if there is a head current and too far out if there is a following current. The existence of the current will not be apparent unless the actual speed over the ground is known. The position of the plotted line relative to the dead reckoning course line is not a reliable guide.

1020. Determining Track Made Good by Plotting Running Fixes

A current oblique to a vessel's course will also result in an incorrect running fix position. An oblique current can be detected by observing and plotting several bearings of the same object. The running fix obtained by advancing one bearing line to the time of the next one will not agree with the running fix obtained by advancing an earlier line. See Figure 1020a. If bearings A, B, and C are observed at five-minute intervals, the running fix obtained by advancing B to the time of C will not be the same as that obtained by advancing A to the time of C, as shown in Figure 1020a.

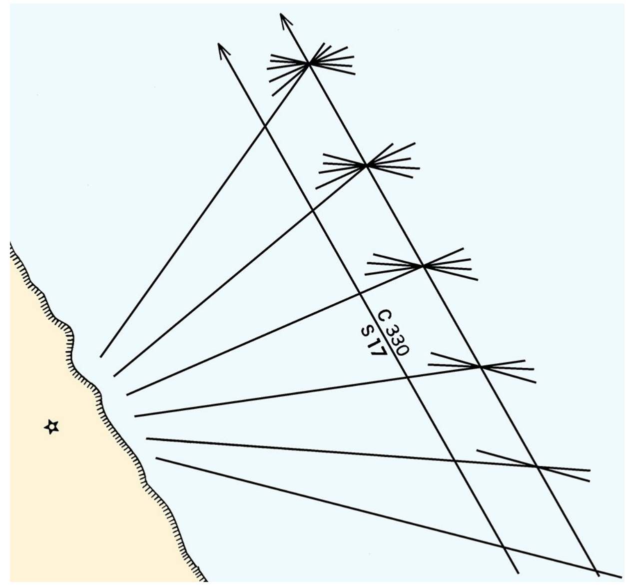


Figure 1019b. A number of running fixes with a following current.

Whatever the current, the navigator can determine the direction of the track made good (assuming constant current and constant course and speed). Observe and plot three bearings of a charted object O. See Figure 1020b. Through O draw XY in any direction. Using a convenient scale, determine points A and B so that OA and OB are proportional to the time intervals between the first and second bearings and the second and third bearings, respectively. From A and B draw lines parallel to the second bearing line, intersecting the first and third bearing lines at C and D, respectively. The direction of the line from C and D is the track made good.

The distance of the line CD in Figure 1020b from the track is in error by an amount proportional to the ratio of the speed made good to the speed assumed for the solution. If a good fix (not a running fix) is obtained at some time before the first bearing for the running fix, and the current has not changed, the track can be determined by drawing a line from the fix, in the direction of the track made good. The intersection of the track with any of the bearing lines is an actual position.

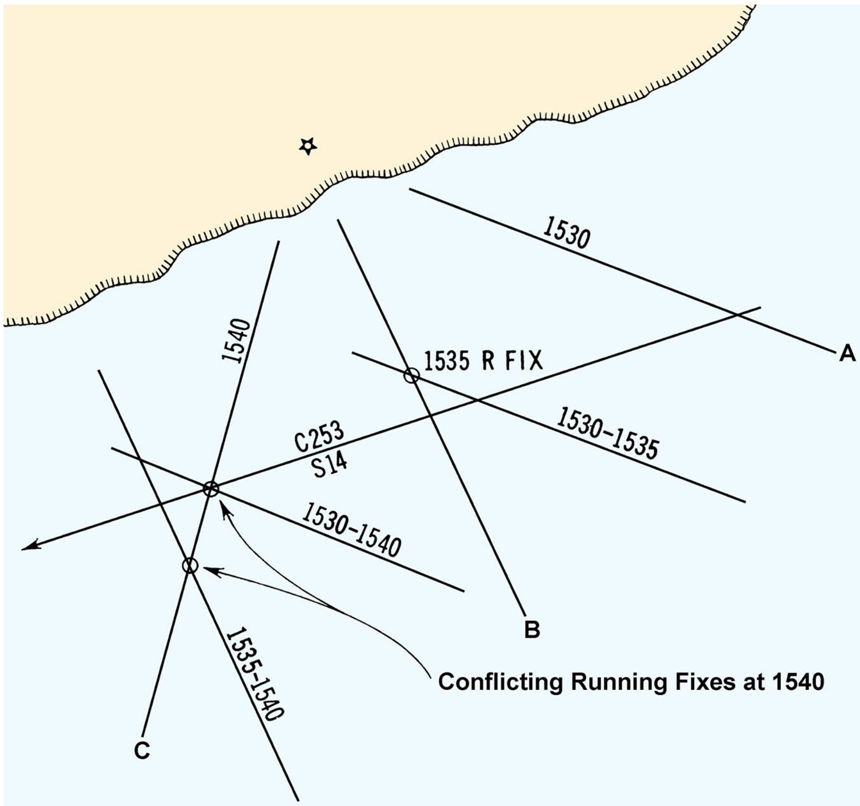


Figure 1020a. Detecting the existence of an oblique current, by a series of running fixes.

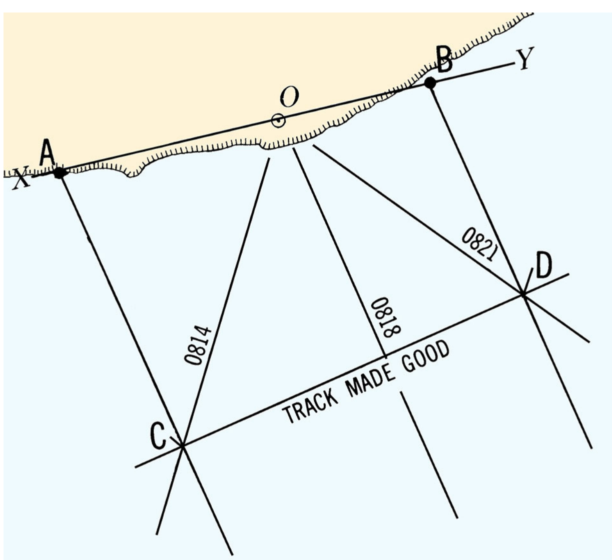


Figure 1020b. Determining the track made good.

1021. Fix by Distance of an Object by Two Bearings (Table 18)

Geometrical relationships can define a running fix. In Figure 1021, the navigator takes a bearing on NAVAID D. The bearing is expressed as degrees right or left of course. Later, at B, s/he takes a second bearing to D; similarly, s/he takes a bearing at C, when the landmark is broad on the beam. The navigator knows the angles at A, B, and C and the distance run between points. The various triangles can be solved using Table 18. From this table, the navigator can calculate the lengths of segments AD, BD, and CD. S/He knows the range and bearing; s/he can then plot an LOP. S/He can then advance these LOP's to the time of taking the CD bearing to plot a running fix.

Enter the table with the difference between the course and first bearing (angle BAD in Figure 1021) along the top of the table and the difference between the course and second bearing (angle CBD) at the left of the table. For each pair of angles listed, two numbers are given. To find the distance from the landmark at the time of the second bearing (BD), multiply the distance run between bearings (in nautical miles) by the first number from Table 18. To find the distance when the object is abeam (CD), multiply the distance run between A and B by the second number from the table. If the run between bearings is exactly 1 mile, the tabulated values are the distances sought.

Example: *A ship is steaming on course 050°, speed 15 knots. At 1130 a lighthouse bears 024°, and at 1140 it bears 359°.*

Required:

- *Distance from the light at 1140.*

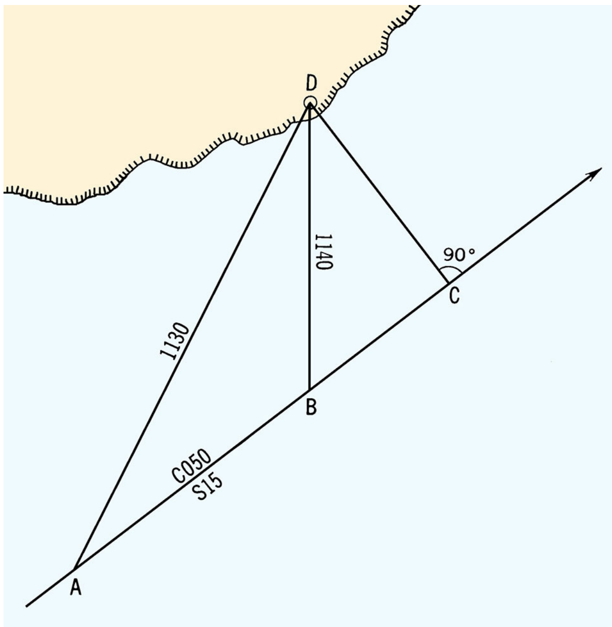


Figure 1021. Triangles involved in a Table 18 running fix.

- *Distance form the light when it is broad on the port beam.*

Solution:

- *The difference between the course and the first bearing (050° – 24°) is 26°, and the difference between the course and the second bearing (050° + 360° - 359°) is 51°.*
- *From* Table 18*, the two numbers (factors are 1.04 and 0.81, found by interpolation.*
- *The distance run between bearings is 2.5 miles (10 minutes at 15 knots).*
- *The distance from the lighthouse at the time of the second bearing is 2.5   1.04 = 2.6 miles.*
- *The distance from the lighthouse when it is broad on the beam is 2.5   0.81 = 2.0 miles.*

Answer: *(1) D 2.6 mi., (2) D 2.0 mi.*

This method yields accurate results only if the helmsman has steered a steady course and the navigator uses the vessel's speed over ground.

MINIMIZING ERRORS IN PILOTING

1022. Common Errors

Piloting requires a thorough familiarity with principles involved, constant alertness, and judgment. A study of groundings reveals that the cause of most is a failure to use or interpret available information. Among the more common errors are:

- Failure to obtain or evaluate soundings
- Misidentification of aids to navigation
- Failure to use available navigational aids effectively
- Failure to correct charts
- Failure to adjust a magnetic compass or keep a table of corrections
- Failure to apply deviation
- Failure to apply variation
- Failure to check gyro and magnetic compass readings regularly
- Failure to keep a dead reckoning plot
- Failure to plot new information
- Failure to properly evaluate information
- Poor judgment
- Failure to use information in charts and navigational publications
- Poor navigation team organization
- Failure to "keep ahead of the vessel"
- Failure to have backup navigational methods in place
- Failure to recognize degradation of electronically obtained LOP's or lat./long. positions
- Failure to slow down when in doubt of ship's location

Some of the errors listed above are mechanical and some are matters of judgment. Conscientiously applying the principles and procedures of this chapter will go a long way towards eliminating many of the mechanical errors. However, the navigator must guard against the feeling that in following a checklist s/he has eliminated all sources of error. A navigator's judgment is just as important as his or her checklists.

1023. Minimizing Errors with a Two Bearing Plot

When measuring bearings from two NAVAIDS, the fix error resulting from an error held constant for both observations is minimized if the angle of intersection of the bearings is 90°. If the observer in Figure 1023a is located at point T and the bearings of a beacon and cupola are observed and plotted without error, the intersection of the bearing lines lies on the circumference of a circle passing through the beacon, cupola, and the observer. With constant error, the angular difference between the bearings of the beacon and the cupola is not affected. Thus, the angle formed at point F by the bearing lines plotted with constant error is equal to the angle formed at point T by the bearing lines plotted without error. From geometry it is known that angles having their apexes on the circumference of a circle and that are subtended by the same chord are equal. Since the angles at points T and F are equal and the angles are subtended by the same chord, the intersection at point F lies on the circumference of a circle passing through the beacon, cupola, and the observer.

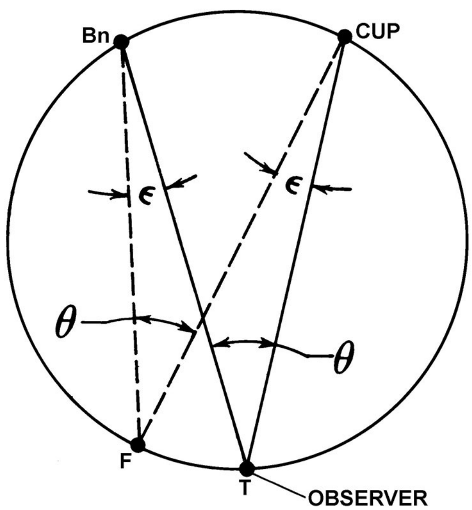


Figure 1023a. Two-bearing plot.

Assuming only constant error in the plot, the direction of displacement of the two-bearing fix from the position of the observer is in accordance with the sign (or direction) of the constant error. However, a third bearing is required to determine the direction of the constant error.

Assuming only constant error in the plot, the two-bearing fix lies on the circumference of the circle passing through the two charted objects observed and the observer. The fix error, the length of the chord FT in Figure 1023b, depends on the magnitude of the constant error $\in$, the distance between the charted objects, and the cosecant of the angle of cut, angle θ. In Figure 1023b,

$$\text{The fix error} = \text{FT} = \frac{\text{BC} \csc \theta}{2}$$

where $\in$ is the magnitude of the constant error, BC is the length of the chord BC, and θ is the angle of the LOP's intersection.

Since the fix error is a function of the cosecant of the angle of intersection, it is least when the angle of intersection is 90°. As illustrated in Figure 1023c, the error increases in accordance with the cosecant function as the angle of intersection decreases. The increase in the error becomes quite rapid after the angle of intersection has decreased to below about 30°. With an angle of intersection of 30°, the fix error is about twice that at 90°.

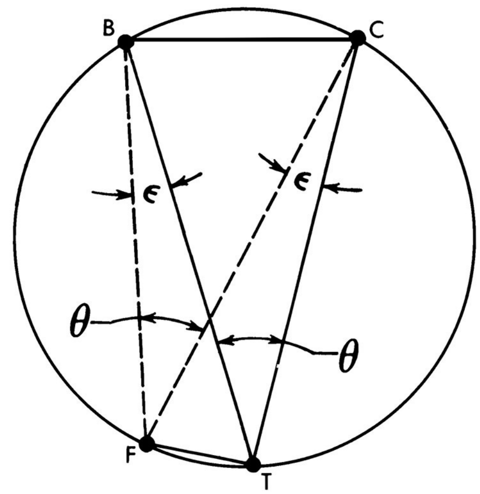


Figure 1023b. Two-bearing plot with constant error.

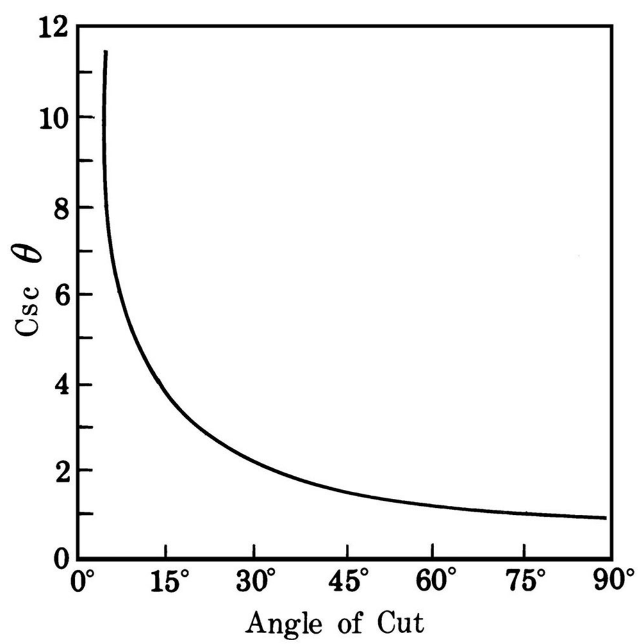


Figure 1023c. Error of two-bearing plot.

1024. Finding Compass Error by Trial and Error

If several fixes obtained by bearings on three objects produce triangles of error of about the same size, there might be a constant error in observing or plotting the bearings. If applying of a constant error to all bearings results in a pinpoint fix, apply such a correction to all subsequent fixes. Figure 1024 illustrates this technique. The solid lines indicate the original plot, and the broken lines indicate each line of position moved 3° in a clockwise direction.

Employ this procedure carefully. Attempt to find and eliminate the error source. The error may be in the gyrocompass, the repeater, or the bearing transmission system. Compare the resulting fix positions with a satellite position, a radar position, or the charted sounding. A high degree of correlation between these three independent positioning systems and an "adjusted" visual fix is further confirmation of a constant bearing error.

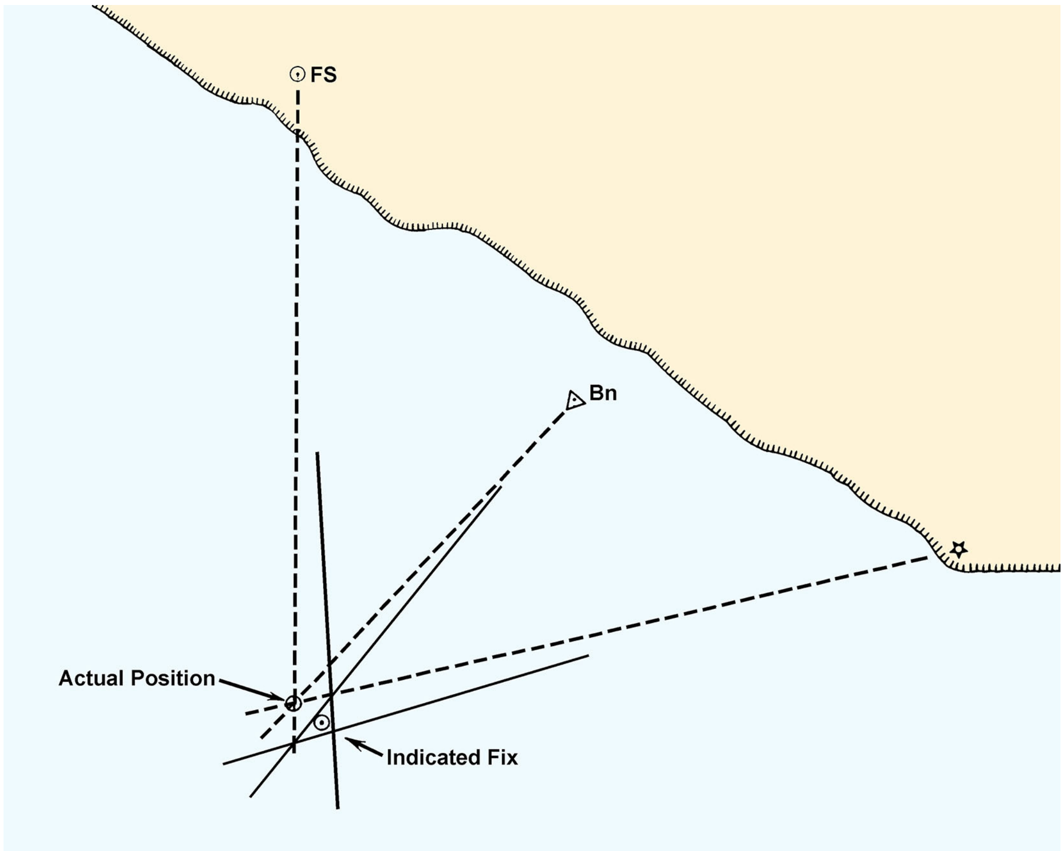


Figure 1024. Adjusting a fix for constant error.

TRAINING

1025. Piloting Simulators

Civilian piloting training has traditionally been a function of both maritime academies and on-the-job experience. The latter is usually more valuable, because there is no substitute for experience in developing judgment. In addition to at-sea training, the US Navy trains Surface Warfare Officers in Navigation and Shiphandling utilizing Conning Officer Virtual Environment (COVE) simulators. Junior Officers to Senior Commanding officers use these frequently throughout their careers to improve their skills and train on the various types of vessels they may serve on. Military vessels in general have a much clearer definition of responsibilities, as well as more people to carry them out, than civilian ships, so training is generally more thorough and targeted to specific skills.

Computer technology has made possible the development of computerized ship simulators by the US Navy and Coast Guard, which allow piloting experience to be gained without risking accidents at sea and without incurring underway expenses. Simulators enable shipboard navigation teams to train and complete required navigation drills. Simulators range from simple micro-computer-based software to a completely equipped ship's bridge with radar, engine controls, 360° horizon views, programmable sea motions, and the capability to simulate almost any navigational situation. See Figure 1025a.

A different type of simulator consists of scale models of ships. The models, actually small craft of about 20-30 feet, have hull forms and power-to-weight ratios similar to various types of ships, primarily supertankers, and the operator pilots the vessel from a position such that his or her view is from the craft's "bridge." These are primarily used in training pilots and masters in docking maneuvers with exceptionally large vessels. For more about scale model shiphandling see Figure 1025b for a link to Port Revel.

The first computer ship simulators came into use in the late 1970s. Several years later the U.S. Coast Guard began

Figure 1025a. Navigational bridge simulator.

Figure 1025b. Port Revel. http://www.portrevel.com.

accepting a limited amount of simulator time as “sea time” for licensing purposes. They can simulate virtually any conditions encountered at sea or in piloting waters, including land, aids to navigation, ice, wind, fog, snow, rain, and lightning. The system can also be programmed to simulate hydrodynamic effects such as shallow water, passing vessels, current, and tugs.

Virtually any type of vessel can be simulated, including tankers, bulkers, container ships, tugs and barges, yachts, and military vessels. Similarly, any given navigational situation can be modeled, including passage through any chosen harbor, river, or passage, convoy operations, meeting and passing situations at sea and in harbors.

Simulators are used not only to train mariners, but also to test feasibility of port and harbor plans and visual aids to navigation system designs. This allows pilots to “navigate” simulated ships through simulated harbors before construction begins to test the adequacy of channels, turning basins, aids to navigation, and other factors.

A full-capability simulator consists of a ship’s bridge which may have motion and noise/vibration inputs, a programmable visual display system which projects a simulated picture of the area surrounding the vessel in both daylight and night modes, image generators for the various inputs to the scenario such as video images and radar, a central data processor, a human factors monitoring system which may record and videotape bridge activities for later analysis, and a control station where instructors control the entire scenario.

Some simulators are part-task in nature, providing specific training in only one aspect of navigation such as radar navigation, collision avoidance, or night navigation.

While there is no substitute for on-the-job training, simulators are extremely cost effective systems which can be run for a fraction of the cost of an actual vessel. Further, they permit trainees to learn from mistakes with no possibility of an accident, they can model an infinite variety of scenarios, and they permit replay and reassessment of each maneuver.

CHAPTER 11

USE OF SEXTANT IN PILOTING

FUNDAMENTAL CONCEPTS

1100. Introduction

The marine sextant has long been an accurate means for fixing a vessel's position in coastal and confined water circumstances. However, with the advent of reliable gyrocompass technologies, followed by the introduction of precise electronic positioning systems like GPS, use of the marine sextant for terrestrial navigation has declined to such an extent that it is seldom employed during normal piloting conditions. This is unfortunate because the sextant can be used to great advantage in situations where other methods or tools, including the gyrocompass, are inadequate. The applications of the sextant during daylight in coastal waters, harbor approaches, and more confined waters may be summarized as follows:

1. fixing to make a safe transit of hazardous waters;
2. fixing to take a specific geographic position;
3. fixing to establish accurately the position of the anchor on anchoring;
4. fixing to determine whether or not the ship is dragging anchor;
5. using horizontal and vertical danger angles;
6. using vertical angles to determine distance off;
7. fixing to determine the positions of uncharted objects, or to verify the positions of charted features;
8. using the sextant to validate the accuracy of navigation by other means.

Because the use of the sextant has declined, many navigators, unfortunately, do not have the proficiency necessary to use it to advantage in those situations where other methods may be inadequate. Proficiency in the use of the sextant can be invaluable in situations where even a small error in either observing or plotting cross bearings could result in navigation blunder.

1101. Three-point problem

Normally, three charted objects are selected for measuring horizontal sextant angles to determine the observer's position, one of the objects being common to each angular measurement. With simultaneous or nearly simultaneous measurements of the horizontal angles between each pair of charted objects, the observer establishes two circles of position. For each pair of objects, there is only one circle which passes through the two objects and the observer's position. Thus, there are two circles, intersecting at two points as shown in Figure 1101a, which pass through the observer's position at *T*.

Since the observer knows that s/he is not at the intersection at *B*, s/he must be at *T*.

The solution of what is known as the **three-point problem** is effected by placing the hairlines of the arms of a plastic three-arm protractor over the three observed objects on the chart as shown in Figure 1101b. With the arms so placed, the center of the protractor disk is over the observer's position on the chart at the time of the measurements.

1102. Solution without three-arm protractor

Although the conventional solution of the three-point problem is obtained by placing the arms of a three-arm protractor over the three observed objects on the chart, the use of the protractor is not necessary. The use of the protractor may not be practicable because of limited space and facilities for plotting, as in a small open boat. Where a common charted object cannot be used in the horizontal angle observations, a means other than the three-arm protractor must be employed to determine the position of the observer. Also, point fixes as obtained from the three-arm protractor can be misleading if the navigator has limited skill in evaluating the strengths of the three-point solutions.

In plotting the three-point fix without a three-arm protractor, the procedure is to find the center of each circle of position, sometimes called **circle of equal angle** (Figure 1102a), and then, about such center, to strike an arc of radius equal to the distance on the chart from the circle center to one of the two objects through which the circle passes. The same procedure is applied to the other pair of objects to establish the fix at the intersection of the two arcs.

Some of the methods for finding the center of a circle of equal angle are described in the following text.

The center of the circle of equal angle lies on the perpendicular bisector of the baseline of the pair of objects. With the bisector properly graduated (Figure 1102b), one need only to place one point of the compasses at the appropriate graduation, the other point at one of the observed objects, and then to strike the circle of equal angle or an arc of it in the vicinity of the DR.

The bisector can be graduated through calculation or by means of either the simple protractor or the three-arm

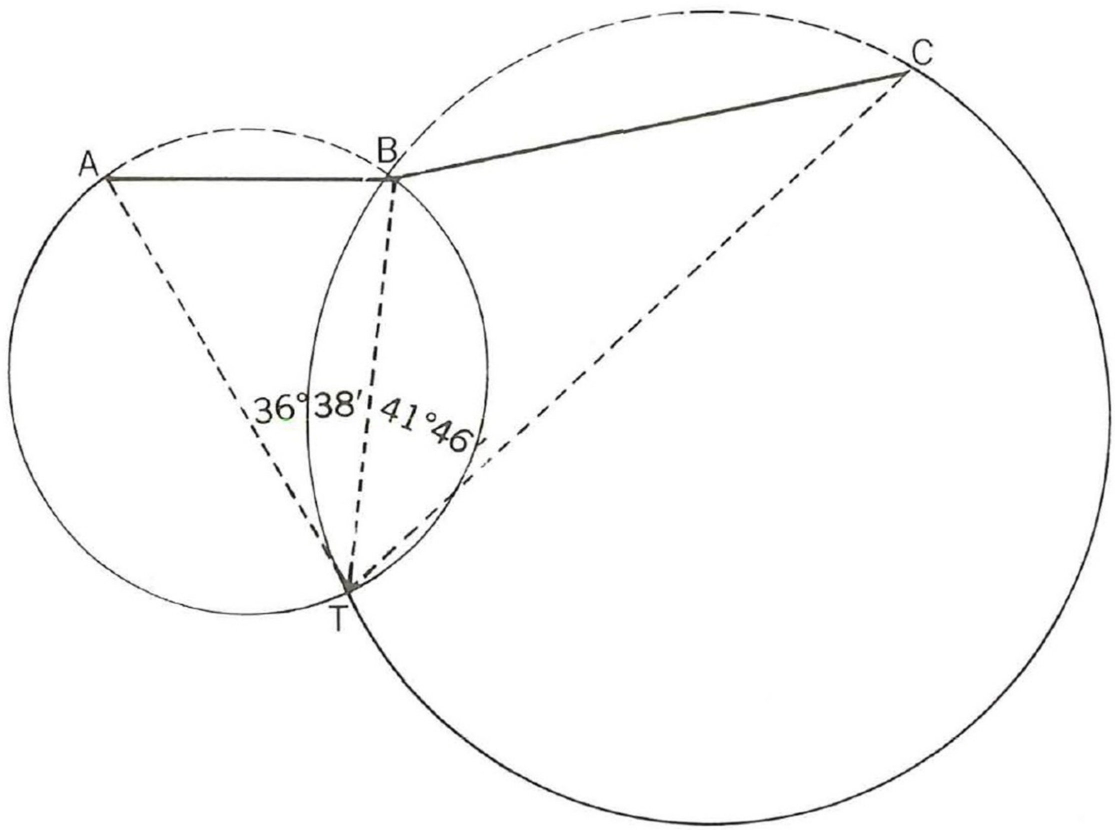


Figure 1101a. Solving the three-point problem.

protractor.

As shown in Figure 1102a, when the observed angle is 90°, the center of the circle of equal angle lies at the center of the baseline or at the foot of the perpendicular bisector of the baseline. When the observed angle is less than 90°, for example 40°, the center of the circle lies on the perpendicular bisector on the same side of the baseline as the observer. When the observed angle is 26°34 ', the center of the circle lies on the bisector at a distance from its foot equal to the distance between the two objects. When the observed angle is greater than 90°, the center of the circle lies on the perpendicular bisector on the side of the baseline opposite from the observer. The center for 100° is the same distance from the baseline as the center for 80°; the center for 110° is the same distance as the center for 70°, etc. These facts can be used to construct a nomogram for finding the distances of circles of equal angle from the foot of the perpendicular for various angles.

From geometry the central angle subtended by a chord is twice the angle with its vertex on the circle and subtended by the same chord. Therefore, when the observed horizontal angle is 30°, the central angle subtended by the baseline is 60°. Or, the angle at the center of the circle between the perpendicular bisector and the line in the direction of one of the observed objects is equal to the observed angle, or 30° as shown in Figure 1102c. The angle at the object between the baseline and the center of the circle on the bisector is 90° minus observed angle, or 60°.

1103. Split Fix

Occasions when a common charted object cannot be used in horizontal angle observations are rare. On these occasions the mariner must obtain what is called a **split fix** through observation of two pairs of charted objects, with no object being common. As with the three-point fix, the mariner will obtain two circles of equal angle, intersecting at two points. As shown in Figure 1103, one of these two intersections will fix the observer's position.

1104. Conning aid

Preconstructed circles of equal angle can be helpful in conning the vessel to a specific geographic position when fixing by horizontal angles. In one application, the vessel is conned to keep one angle constant, or nearly constant, in order to follow the circumference of the associated circle of equal angle to the desired position; the other angle is changing rapidly and is approaching the value for the second circle of equal angle passing through the desired position.

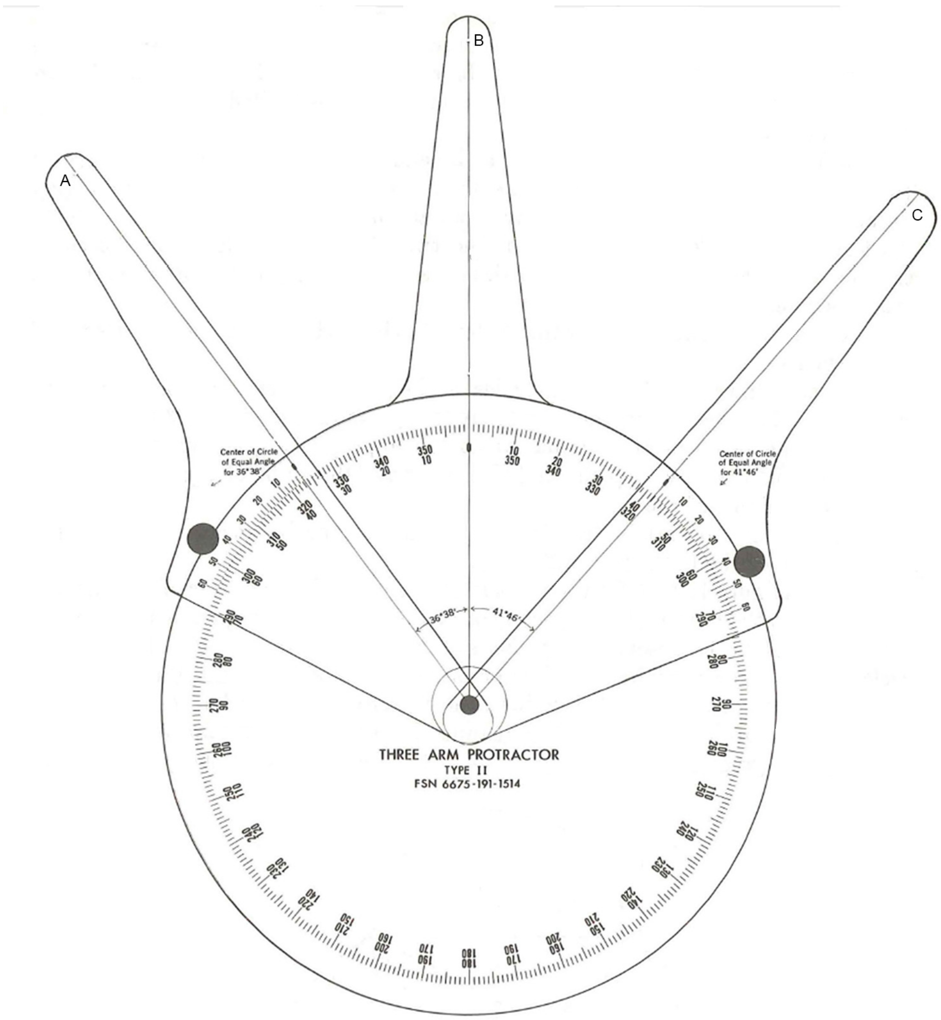


Figure 1101b. Use of the three-armed protractor.

1105. Strength of three-point fix

Although an experienced navigator can readily estimate the strength of a three-point fix, and is able to select the objects providing the strongest fix available quickly, others often have difficulty in visualizing the problem and may select a weak fix when strong ones are available. The following generally useful (but not infallible) rules apply to selection of charted objects to be observed:

1. The strongest fix is obtained when the observer is inside the triangle formed by the three objects. And in such case the fix is strongest where the three objects form an equilateral triangle (Figure 1105, view A), the observer is at the center, and the objects are close to the observer.

2. The fix is strong when the sum of the two angles is equal to or greater than 180 ° and neither angle is less than 30°. The nearer the angles are equal to each other, the stronger is the fix (view B).

3. The fix is strong when the three objects lie in a straight line and the center object is nearest the observer (view C).

4. The fix is strong when the center object lies between the observer and a line joining the other two, and the center object is nearest the observer (view D).

5. The fix is strong when two objects a considerable distance apart are in range and the angle to the third object is greater than 45 ° (view E).

6. Small angles should be avoided as they result in weak fixes in most cases and are difficult to plot. However, a strong fix is obtained when two objects are nearly in range and the nearest one is used as the common object. The small angle must be measured very accurately, and the position of the two objects in range must be very accurately plotted. Otherwise, large errors in position will result. Such fixes are strong only when the common object is nearest the observer. The fix will become very weak where the observer moves to a position where the distant object is the common object (view F).

7. A fix is strong when at least one of the angles chang-

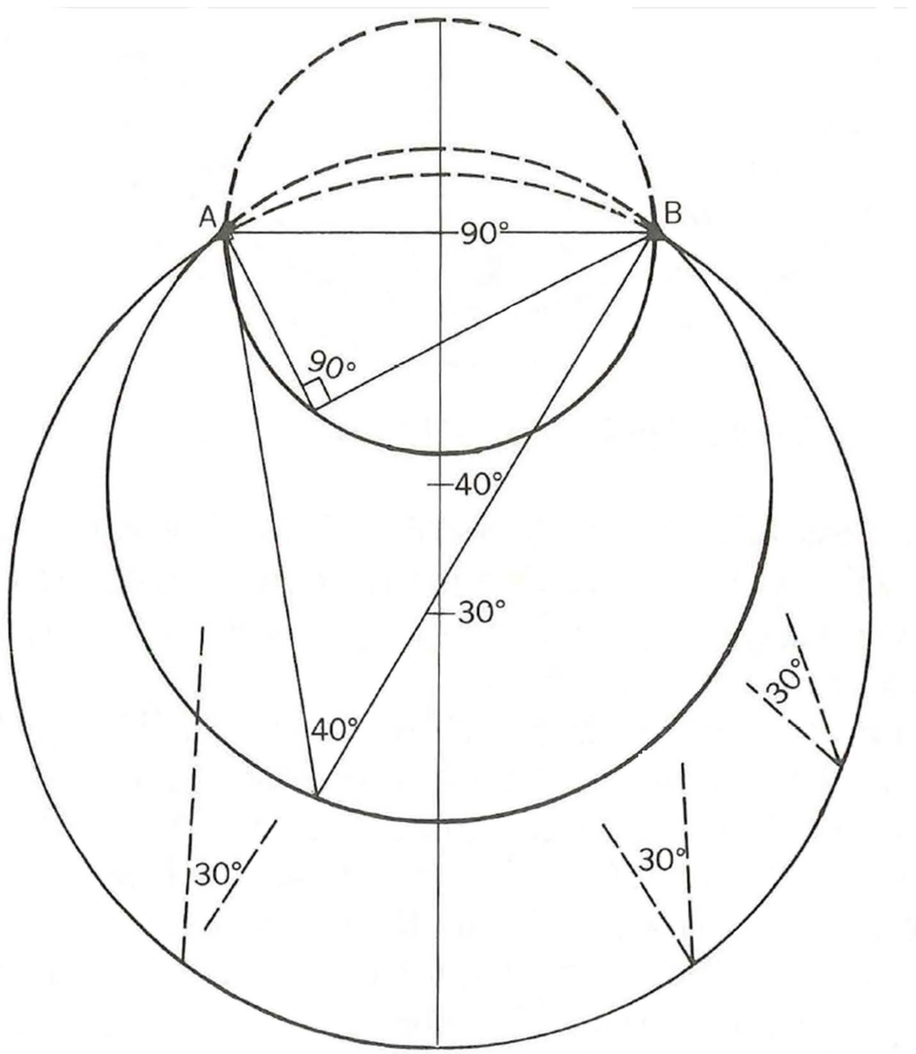


Figure 1102a. Circles of equal angle.

es rapidly as the vessel moves from one location to another.

8. The sum of the two angles should not be less than 50°; better results are obtained when neither angle is less than 30 °.

9. Do not observe an angle between objects of considerably different elevation. Indefinite objects such as tangents, hill-tops, and other poorly defined or located points should not be used. Take care to select prominent objects such as major lights, church spires, towers or buildings which are charted and are readily distinguished from surrounding objects.

Beginners should demonstrate the validity of the above rules by plotting examples of each and their opposites. It should be noted that a fix is strong if, in plotting, a slight movement of the center of the protractor moves the arms away from one or more of the stations, and is weak if such movement does not appreciably change the relation of the arms to the three points. An appreciation of the accuracy required in measuring angles can be obtained by changing one angle about five minutes in arc in each example and noting the resulting shift in the plotted positions;

The **error of the three-point fix** will be due to:

1. error in measurement of the horizontal angles;
2. error resulting from observer and observed objects not lying in a horizontal plane;
3. instrument error; and
4. plotting error.

The magnitude of the error varies directly as the error in measurement, the distance of the common object from the observer, (*D*) and inversely as the sine function of the angle of cut (*?*). The magnitude of the error also depends upon the following ratios:

1. The distance to the object to the left of the observer divided by the distance from this object to the center object (r_1).

2. The distance to the object to the right of the observer divided by the distance from this object to the center object

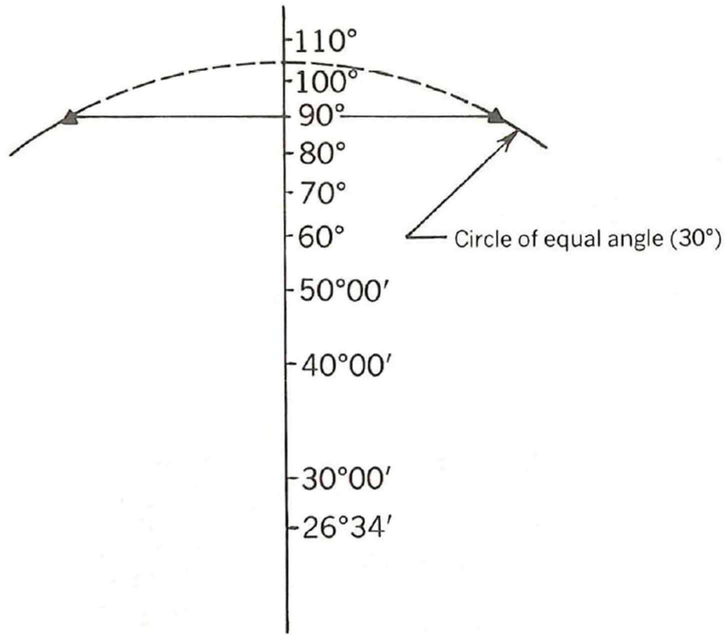


Figure 1102b. Graduated perpendicular bisector.

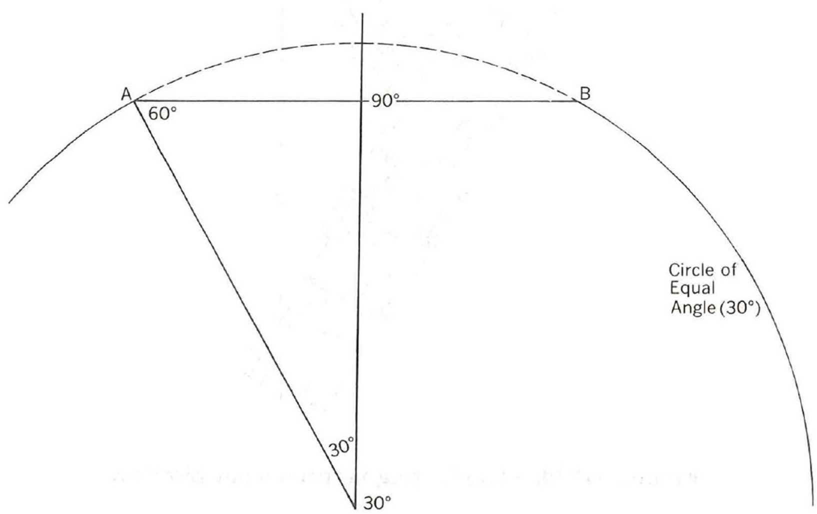


Figure 1102c. Circle of equal angle (30°).

(r_2).

Assuming that each horizontal angle has the same error (*?*), the magnitude of the error (*E*) is expressed in the formula

$$E = \frac{\alpha D}{\sin\theta}\sqrt{r_1^2 + r_2^2 + (2r_1)r_2\cos\theta}$$

where error in measurement (*?*) is expressed in radians.

The magnitude of the error (*E*) is expressed in the formula

$$E = \frac{0.00029\alpha D}{\sin\theta}\sqrt{r_1^2 + r_2^2 + (2r_1)r_2\cos\theta}$$

where error in measurement (?) is expressed in minutes of arc.

To avoid mistakes in the identification of charted objects observed, either a check bearing or a check angle should be used to insure that the objects used in observation and plotting are the same.

1106. Avoiding the swinger

Avoid a selection of objects which will result in a "**revolver**" or "**swinger**"; that is, when the three objects observed on shore and the ship are all on, or near, the cir-

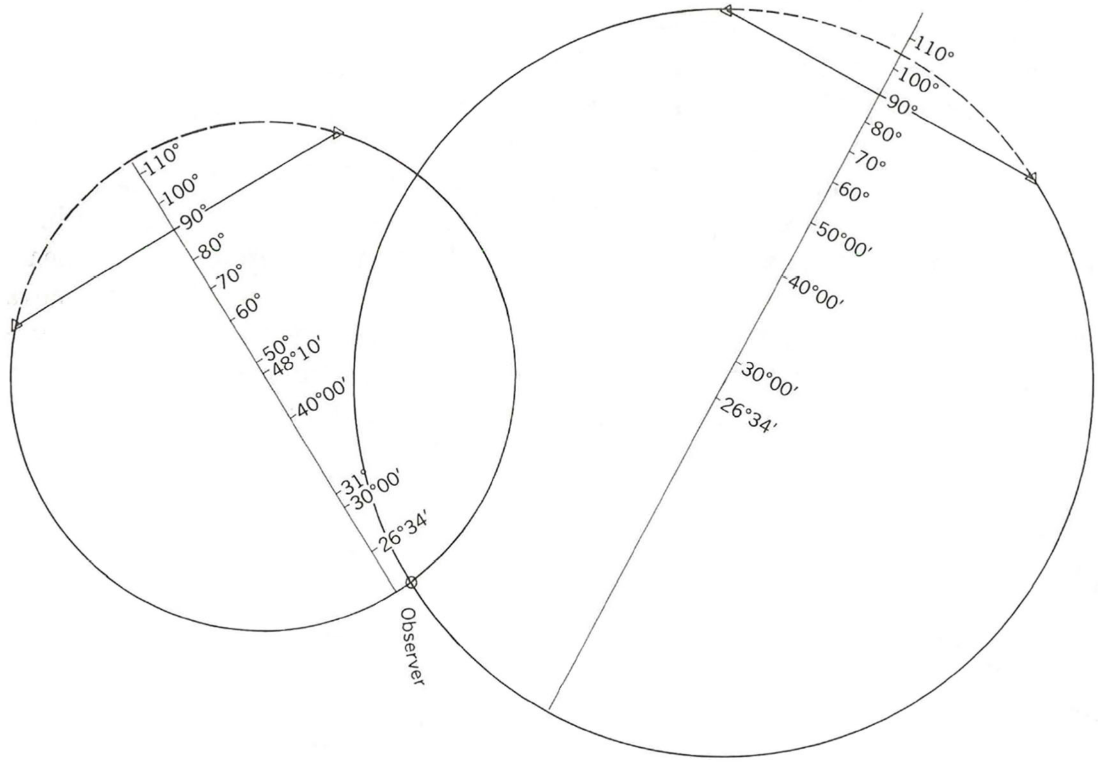


Figure 1103. Split fix.

cumference of a circle (Figure 1106). In such a case the ship's position is indeterminate by three-point fix.

If *bearings* as plotted are affected by unknown and uncorrected compass error, the bearing lines may intersect at a point when the objects observed ashore and the ship are all on, or near, the circumference of a circle.

1107. Cutting in uncharted objects

To cut in or locate on the chart uncharted objects, such as newly discovered offshore wrecks or objects ashore which may be useful for future observations, proceed as follows:

1. Fix successive positions of the ship or ship's boat by three-point fixes, i.e., by horizontal sextant angles. At each fix, simultaneously measure the sextant angle between one of the objects used in the fix and the object to be charted (Figure 1107b). For more accurate results, the craft from which the observations are made should be either lying to or proceeding slowly.

2. For best results, the angles should be measured simultaneously. If verification is undertaken, the angles observed should be interchanged among observers.

3. The fix positions should be selected carefully to give strong fixes, and so that the cuts to the object will provide a good intersection at the next station taken for observations. A minimum of three cuts should be taken.

An alternative procedure is to select observing positions so that the object to be charted will be in range with one of the charted objects used to obtain the three-point fix (Figure 1107a). The charted objects should be selected to provide the best possible intersections at the position of the uncharted object.

1108. Horizontal and vertical danger angles

A vessel proceeding along a coast may be in safe water as long as it remains a minimum distance off the beach. This information may be provided by any means available. One method useful in avoiding particular dangers is the use of a **danger angle**. Refer to Figure 1108. A ship is proceeding along a coast on course line *AB*, and the captain wishes to remain outside a danger *D*. Prominent landmarks are located at *M* and *N*. A circle is drawn through *M* and *N* and tangent to the outer edge of the danger. If *X* is a point on this circle, angle *MXN* is the same as at any other point on the circle (except that part between *M* and *N*). Anywhere within the circle the angle is *larger* and anywhere outside the circle it is *smaller*. Therefore, any angle smaller than *MXN* indicates a safe position and any angle larger than *MXN* indicates possible danger. Angle *MXN* is therefore a maximum **horizontal danger angle**. A minimum horizontal danger angle is used when a vessel is to pass *inside* an offlying danger, as at *D′* in Figure 1108. In this case the circle is drawn through *M* and *N* and tangent to the *inner* edge of the danger area. The angle is kept larger than *MYN*. If a vessel is to pass between two danger areas, as in Figure 1108, the horizontal angle should be kept smaller than *MXN* but

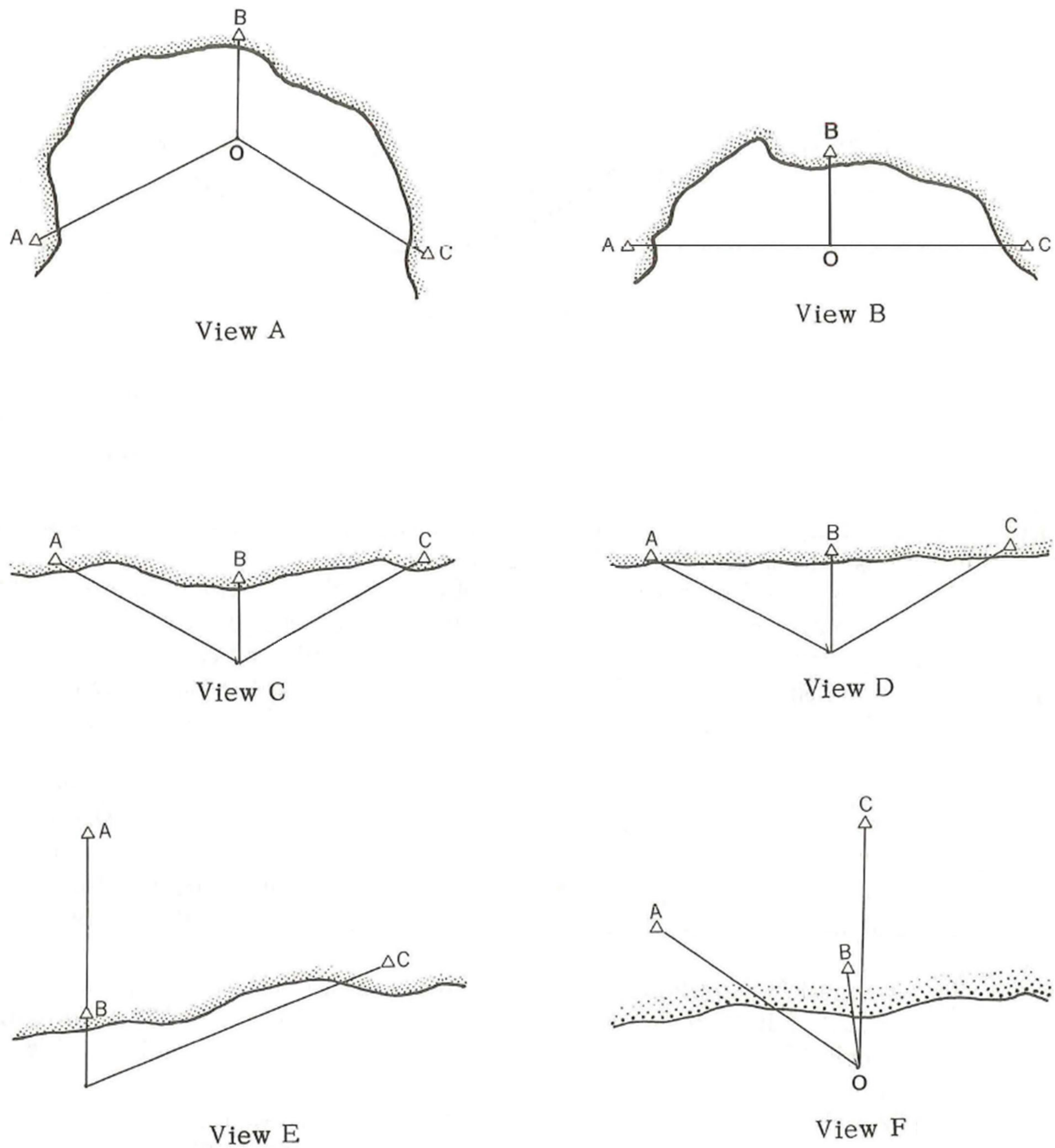


Figure 1105. Strengths of three-point fixes.

larger than *MYN*. The minimum danger angle is effective only while the vessel is inside the larger circle through *M* and *N*. Bearings on either landmark might be used to indicate the entering and leaving of the larger circle. A margin of safety can be provided by drawing the circles through points a short distance off the dangers. Any method of measuring the angles, or difference of bearing of *M* and *N*, can be used. Perhaps the most accurate is by horizontal sextant angle. If a single landmark of known height is available, similar procedure can be used with a **vertical danger angle** between top and bottom of the object. In this case the charted position of the object is used as the center of the circles.

1109. Distance by vertical angel

Table 16 (Distance by Vertical Angle) provides means for determining the distance of an object of known height above sea level. The vertical angle between the top of the object and the visible (sea) horizon (the sextant altitude) is measured and corrected for index error and dip only. If the visible horizon is not available as a reference, the angle should be measured to the bottom of the object, and dip short of the horizon (table. 15) used in

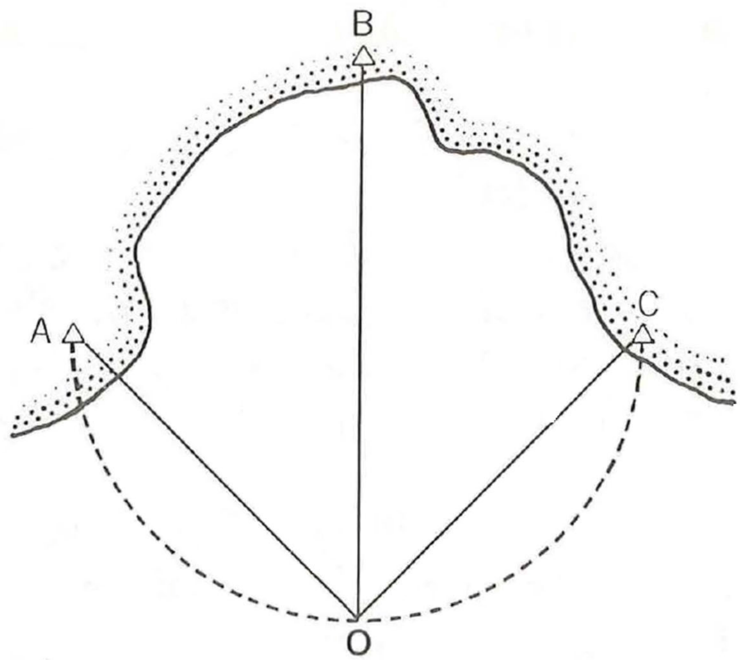


Figure 1106. Revolver or swinger.

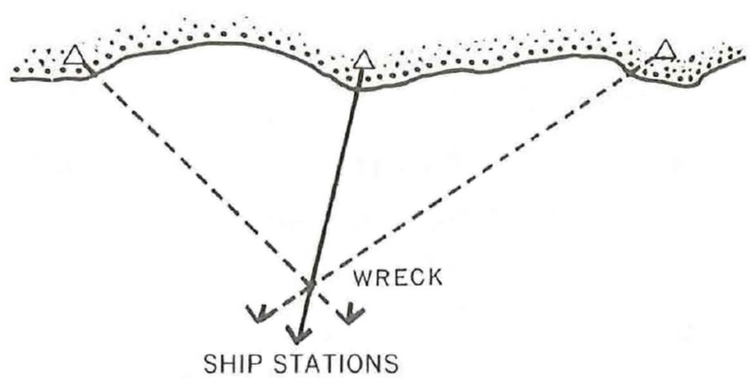


Figure 1107a. On range method.

place of the usual dip correction. This may require several approximations of distance by alternate entries of tables 16 and 15 until the same value is obtained twice. The table is entered with the difference in the height of the object and the height of eye of the observer, in feet, and the corrected vertical angle; and the distance in nautical miles is taken directly from the table. An error may be introduced if refraction differs from the standard value used in the computation of the table. See the Explanation of Tables section in Volume II for more details.

1110. Evaluation

As time and conditions permit, it behooves the navigator to use the sextant to evaluate the accuracy of navigation by other means in pilot waters. Such accuracy comparisons tend to provide navigators with better appreciation of the limitations of fixing by various methods in a given piloting situation.

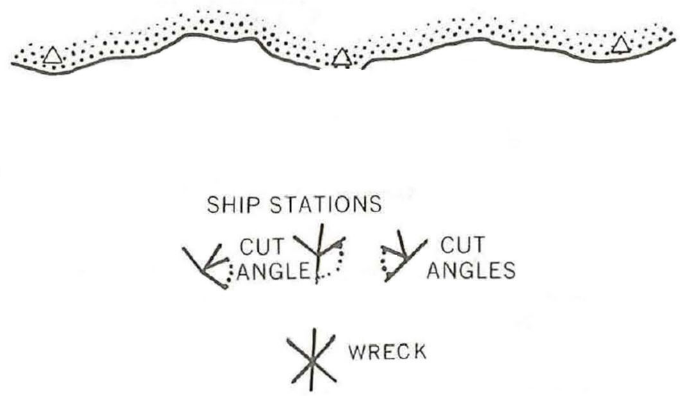


Figure 1107b. Cutting in uncharted objects.

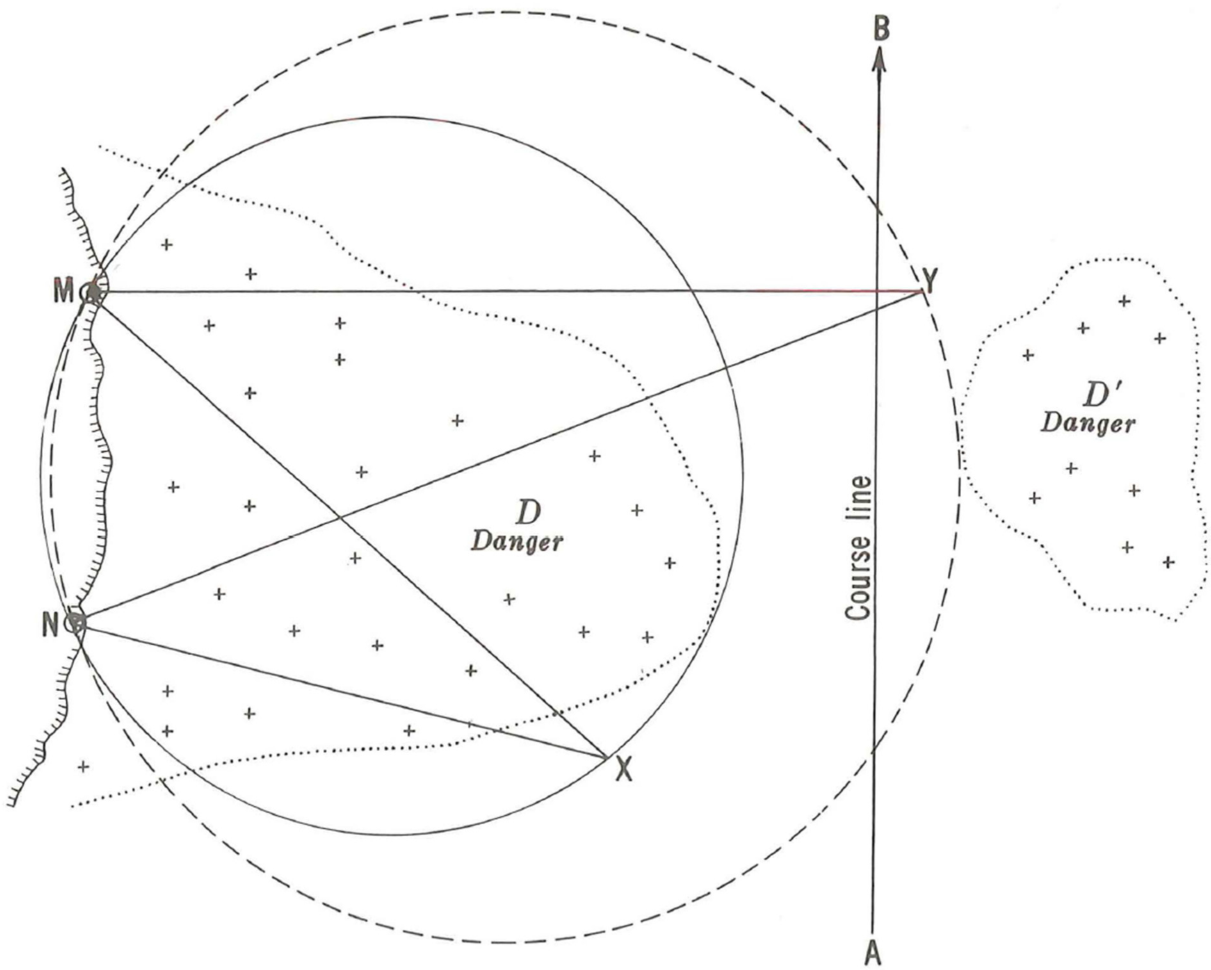


Figure 1108. Horizontal danger angles.

CHAPTER 12

THE SAILINGS

INTRODUCTION

1200. Introduction

Dead reckoning involves the determination of a present or future position by projecting the vessel's course and distance run from a known position. A closely related problem is that of finding the course and distance from one known point to another. For short distances, these problems are easily solved directly on charts, but for trans-oceanic distances, a purely mathematical solution is often a better method. Collectively, these methods are called **The Sailings**.

Navigational computer programs and calculators commonly contain algorithms for computing all of the problems of the sailings. This chapter discusses basic calculation methods and tabular solutions. Navigators can also refer to National Geospatial-Intelligence Agency (NGA) *Pub. 151, Distances Between Ports*, for distances along normal ocean routes. Pilot charts also offer some track and distance information.

Because most commonly used formulas for the sailings are based on rules of spherical trigonometry and assume a perfectly spherical Earth, there may be inherent errors in the calculated answers. Also, differences in rounding practices will result in slightly varying solutions. Errors of a few miles over distances of a few thousand miles can be expected. These will generally be much less than errors due to currents, steering error, and leeway.

To increase the accuracy of these calculations, one would have to take into account the oblateness of the Earth. Formulas exist which account for oblateness, reducing these errors to less than the length of the typical vessel using them, but far larger errors can be expected on any voyage of more than a few day's duration.

There are two types of Sailings: Great Circle and Rhumb Lines. Both will be described in detail in this chapter.

1201. Terms and Definitions

In solutions of the sailings, the following quantities are used:

1. **Arc min**. Minutes of arc; for example, 234 arc min is usually indicated as 234' in formulae.
2. **Course (Cn)**. The vessel's true course, or a track-line's true course, as measured from 000°-360° T.
3. **Course Angle (C)**. The angular direction measured clockwise or counterclockwise from 000° through 090° or 180°. The reference direction (north or south) will be the prefix and the direction of measurement (east or west) will be the suffix. The parameters and procedure for labeling the prefix and suffix differs with the type of sailing. C is normally expressed as N/S xxx° E/W and converted to true course by reading "the true course is xxx° E/W of N/S."
4. **Departure (p or Dep.)**. The distance (in nautical miles) between two meridians at any given parallel of latitude; differentiated from DLo which is an angular measure of the same arc and does not change with latitude. Departure (p) between two meridians decreases with the cosine of the latitude as latitude increases. At the equator, departure is equal to DLo (in minutes). Departure becomes zero at the poles. Departure must be marked E or W depending on the direction it was measured. The relationship between departure and DLo is p = (cos L) DLo.
5. **Difference of latitude (*l* or DLat or ΔL)**. The shorter arc of any meridian between the parallels of two places, expressed in angular measure. The difference in latitude between L1 and L2, usually expressed in minutes of arc.
6. **Difference of longitude (DLo or ΔLong or $\Delta\lambda$)**. The shorter arc of a parallel between the meridians of two places, expressed in angular measure. The difference in longitude between two points, usually expressed in minutes of arc; Differentiated from p (departure) which is the same arc measured in nautical miles. DLo will remain the same regardless of latitude. DLo_v is the difference in longitude between the point of departure and the great circle vertex. DLo_{vx} is the difference in longitude between the great circle vertex and a point on the great circle track.
7. **Distance (D or Dist.)**. Distance in nautical miles (nm) of 6,076.1 feet or 1,852 meters. D_v is the great circle distance to the vertex from the point of departure. D_{vx} is the distance from the vertex to a

point on the great circle track.

8. **Latitude (L)**. The latitude of the point of departure is designated L_l; that of the destination, L_2; middle (mid) or mean latitude, L_m; latitude of the vertex of a great circle, L_v; and latitude of any point on a great circle, L_x.
9. **Longitude** (λ). The longitude of the point of departure is designated λ_1; that of the point of arrival or the destination, λ_2; of the vertex of a great circle, λ_v; and of any point on a great circle, λ_x.
10. **Mean latitude (L_m)**. Half the arithmetical sum of the latitudes of two places on the same side of the equator.
11. **Meridional parts (M)**. The meridional parts of the point of departure are designated M_l, and of the point of arrival or the destination, M_2. Meridional Parts can be found in Table 6 in Volume 2 with the latitude as an entering value.
12. **Meridional difference (m)**. The mathematical difference between the tabular values of M_2 and M_l.
13. **Middle or mid latitude (L_m)**. The latitude exactly mid-way between the point of departure and point of arrival latitudes. The latitude at which the arc length of the parallel separating the meridians passing through two specific points is exactly equal to the departure (p) in proceeding from one point to the other by mid-latitude sailing. The mean latitude is used when there is no practicable means of determining the middle latitude.

KINDS OF SAILINGS

1202. Great Circles

A **great circle** is the intersection of the surface of a sphere and a plane through the center of the sphere. It is the largest circle that can be drawn on the surface of the sphere and is the shortest distance, along the surface, between any two points on the sphere. Any two points are connected by only one great circle, unless the points are antipodal (180° apart), in which case an infinite number of great circles pass through them. Every great circle bisects every other great circle. Thus, except for the equator, every great circle lies half in the northern hemisphere and half in the southern hemisphere. Any two points 180° apart on a great circle have the same numerical latitude, but contrary names, and are 180° apart in longitude.

The point of greatest latitude on a great circle is called the **vertex**, and there is a vertex in each hemisphere, 180° apart. At the vertex, the great circle is tangent to a parallel of latitude and the direction along the great circle would be exactly due east or west. On each side of these vertices the direction changes progressively until the intersection with the equator is reached, 90° away, where the great circle crosses the equator at an angle equal to the latitude of the vertex. As the great circle crosses the equator, its change in direction reverses, again approaching east/west, which it reaches at the next vertex.

Great circle sailing involves the solution of courses, distances, and points along a great circle between two points. Great circle sailing takes advantage of the shorter distance along the great circle between two points, as compared to the longer rhumb line. The arc of the great circle between the points of departure and arrival is called the **great circle track**. The rhumb line appears the more direct route on a Mercator chart because of chart distortion. Along any intersecting meridian the great circle crosses at a higher latitude than the rhumb line. Because the great circle crosses meridians at higher latitudes, where the distance between them is less, the great circle route is shorter than the rhumb line.

The savings in distance offered by a great circle route, as compared to a rhumb line track, increases as

1. the latitude increases (the farther from the equator the route is)
2. as the difference of latitude between the two points decreases (the more easterly/westerly the track), and
3. as the difference of longitude increases (the longer the route is). Of course any track that runs exactly due north or south, or lies along the equator is itself a great circle and would be coincident with the rhumb line track.

On a Mercator projection, a great circle appears as a sine curve, concave to the equator, extending equal distances on each side of the equator. The rhumb line connecting any two points of the great circle on the same side of the equator is a chord of the curve. If the two points are on opposite sides of the equator, the direction of curvature of the great circle relative to the rhumb line changes at the equator. The rhumb line and great circle may intersect each other, and if the points are equal distances on each side of the equator, the intersection takes place at the equator. Along any intersecting meridian, the great circle crosses at a higher latitude than the rhumb line. If the two points are on opposite sides of the equator, the direction of curvature of the great circle relative to the rhumb line changes at the equator.

Despite the constant course changes required to follow a great circle, if the great circle could be followed exactly, the destination would always be dead ahead (on the sphere). Since a great circle (other than a meridian or the equator) is a curved line whose true direction changes continually, the navigator does not attempt to follow it exactly. Instead, a number of waypoints are selected along the great circle, rhumb lines are drawn between the waypoints, and the vessel is steered along these rhumb lines. The number of points to use is a matter of personal preference. A large number of points provides a closer approximation to the great circle, but requires more frequent course changes. As a general rule, 5° of longitude is a convenient length. This method does not provide legs of equal length, but under normal conditions, this is acceptable. Care must be taken to apply the correct variation and deviation to magnetic compass headings as the vessel changes location and heading along the great circle route.

The decision to use a great circle sailing depends upon several factors. The savings in distance should be worth the additional effort, and of course the great circle route cannot cross land, nor should it carry the vessel into dangerous waters. If a vessel finds herself considerably off the desired great circle track, it may be preferable to generate a new great circle route for the remainder of the voyage, rather than return to the original route.

1203. Altering a Great Circle Track to Avoid Obstructions

Usually, great circle tracks are followed from an offshore point of departure, near a sea buoy for example, to a similar offshore point of arrival. However, obstructions such as land, ice, or prohibited areas may make following the great circle for the entire voyage impossible. One may also alter a direct route in order to take advantage of favorable winds or currents. If the great circle route needs to be modified the navigator may follow the great circle to the obstruction then follow a rhumb line course (or several) until clear of the obstruction, and then follow a great circle to the destination. One could also sail great circle to a point near the obstruction and then a different great circle from that point to the destination. Another solution is to use a composite sailing.

1204. Rhumb Lines

A rhumb line makes the same angle with all meridians it crosses and appears as a straight line on a Mercator chart. The principal advantage of a rhumb line is that it maintains a constant true direction and a ship following the rhumb line between two places does not change its true course. It is adequate for most purposes of navigation, bearing lines (except long bearing lines such as are obtained by radio bearings), and course lines both being plotted on a Mercator chart as rhumb lines, except in high latitudes.

Rhumb line sailings account for the spherical nature of the path using various mathematical formulae, and will yield different results for courses, distances and positions depending on the type of sailing used.

The types of rhumb line sailings are:

1. **Parallel sailing** is the interconversion of departure and difference of longitude when a vessel is proceeding due east or due west and thus sailing along a parallel of latitude.

2. **Plane sailing** solves problems involving a single course and distance, difference of latitude, and departure, in which the Earth is regarded as a plane surface. This method, therefore, provides solution for latitude of the point of arrival, but not for longitude of the arrival point. To calculate the longitude, the spherical sailings are necessary. Because of the assumption that the Earth is flat, plane sailing is not intended for distances of more than a few hundred miles.

3. **Mercator sailing** provides a mathematical solution of the plot as made on a Mercator chart. It is similar to plane sailing, but uses meridional difference and difference of longitude in place of difference of latitude and departure, respectively.

4. **Middle- (or mid-) latitude sailing** uses the mean latitude for converting departure to difference of longitude when the course is not due east or due west and it is assumed the course is steered at the mid latitude.

5. **Traverse sailing** combines the plane sailing solutions when there are two or more courses and determines the equivalent course and distance made good by a vessel steaming along a series of rhumb lines.

6. **Meridian sailing** describes a vessel is sailing due north or south along a meridian of longitude. No solutions are necessary because there is no departure or difference in longitude. Though course is constant, it actually is also a great circle sailing.

1205. Composite Sailing

A **composite sailing** (a combination of great circle and rhumb line tracks) is planned as a great circle route with rhumb line portions inserted as required to sail along a desired parallel of latitude, usually to avoid a navigational danger such as ice, land, or inclement weather. The composite track consists of a great circle from the point of departure tangent to a limiting parallel of latitude, a course line due east or west along the parallel of latitude, and a great circle tangent to the limiting latitude and to the destination.

Solution is made most easily by means of a great circle chart. Composite sailing only applies when the vertex lies between the departure and arrival points.

GREAT CIRCLE SAILING SOLUTIONS

1206. Great Circle Sailing by Chart

The graphic solution of great circle problems involves the use of gnomonic projection charts. NGA publishes several gnomonic projections covering the principal navigable waters of the world. On these great circle charts, any straight line is a great circle. Gnomonic charts however, are not conformal; therefore, the navigator cannot directly measure directions or distances as on a Mercator chart.

The usual method of using a gnomonic chart is to plot the route and pick points along the track every 5° of longitude using the latitude and longitude scales in the immediate vicinity of each point. These points are then transferred to a Mercator chart and connected by rhumb lines. The course and distance for each leg can then be measured on the Mercator chart, and the points entered as waypoints. See Figure 1206. A projection on which a straight line is approximately a great circle can be used in place of a gnomonic chart with negligible error. If the projection is conformal, such as a Lambert conformal chart, measurement of course and distance of each leg can be made directly on the chart.

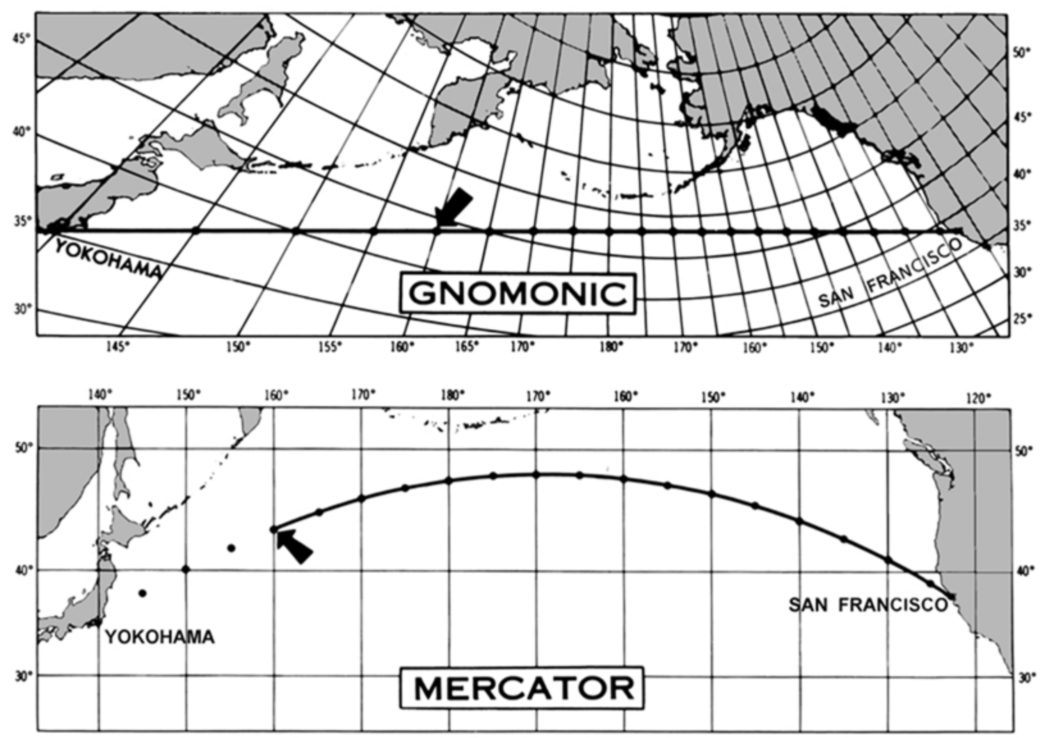


Figure 1206. Constructing a great circle track on a Mercator projection.

1207. Great Circle Sailing by *Sight Reduction Tables*

Any method of solving a spherical triangle can be used for solving great circle sailing problems. The point of departure replaces the assumed position of the observer, the destination replaces the geographical position of the body, the difference of longitude replaces the meridian angle or local hour angle, the initial course angle replaces the azimuth angle, and the great circle distance replaces the zenith distance (90° - altitude). See Figure 1207b. Therefore, any table of azimuths (if the entering values are meridian angle, declination, and latitude) can be used for determining initial great circle course. Tables which solve for altitude, such as *Pub. No. 229*, can be used for determining great circle distance. The required distance is 90° - altitude. Explanation can be found on pages xx-xxii in the introductions section of *Pub. No. 229*. Pub. No. 229 is available for download through the link found in Figure 1207a.

Figure 1207a. Pub No. 229.
https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_st=&_pageLabel=msi_portal_page_62&pubCode=0013

For some inspection tables like those in *Pub. No. 229*, the given combination of L_1, L_2, and DLo may not be tabulated. In this case reverse the name of L_2 and use 180° - DLo for entering the table. The required course angle is then 180° minus the tabulated azimuth, and distance is 90° plus the altitude. If neither combination can be found, solution cannot be made by that method. By interchanging L_1 and L_2, one can find the supplement of the final course angle.

Solution by table often provides a rapid approximate check, but accurate results usually require triple interpolation.

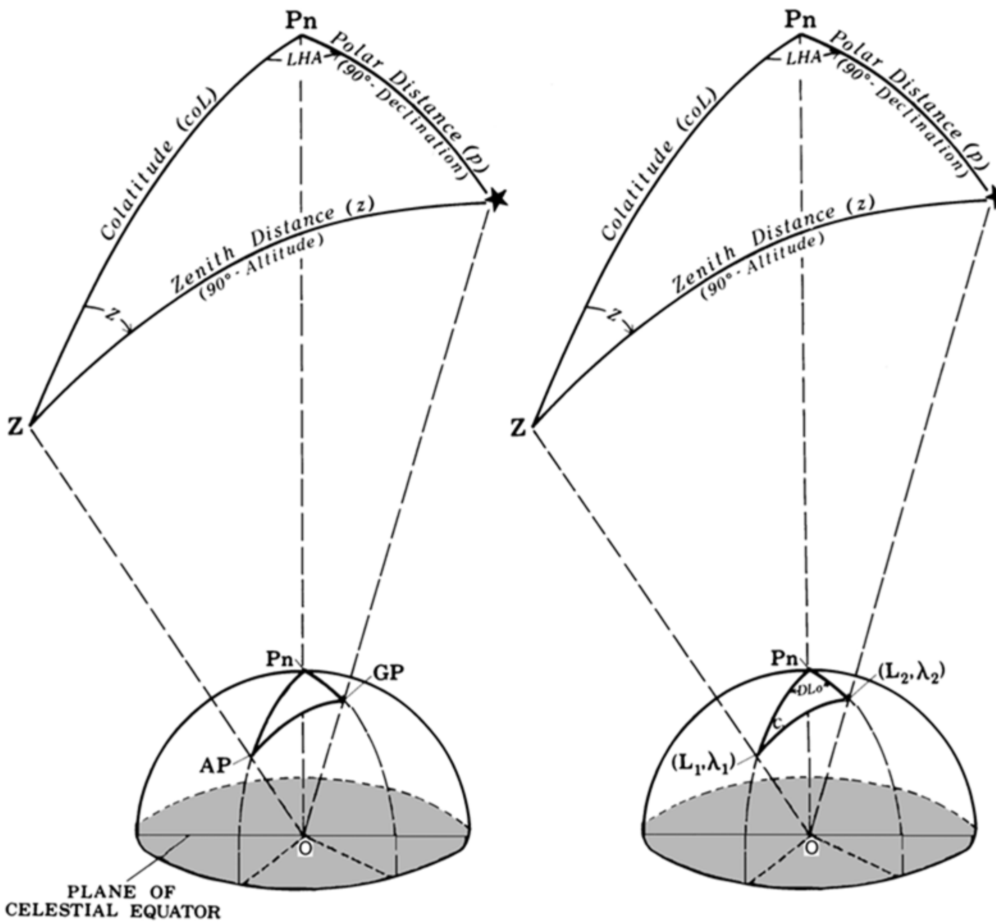


Figure 1207b. Adapting the astronomical triangle to the navigational triangle of great circle sailing.

Except for *Pub. No. 229*, inspection tables do not provide a solution for points along the great circle. *Pub. No. 229* provides solutions for these points only if interpolation is not required.

By entering *Pub. No. 229* with the latitude of the point of departure as latitude, latitude of destination as declination, and difference of longitude as LHA, the tabular altitude and azimuth angle may be extracted and converted to great circle distance and course. As in sight reduction, the tables are entered according to whether the name of the latitude of the point of departure is the same as or contrary to the name of the latitude of the destination (declination). If the values correspond to those of a celestial body above the celestial horizon, 90° minus the arc of the tabular altitude becomes the distance; the tabular azimuth angle becomes the initial great circle course angle. If the respondents correspond to those of a celestial body below the celestial horizon (meaning the Contrary/Same (C/S) line has been crossed), the arc of the tabular altitude plus 90° becomes the distance, and the supplement of the tabular azimuth angle becomes the initial great circle course angle.

When the C/S line is crossed in either direction, the altitude becomes negative and the body lies below the celestial horizon. For example: If the tables are entered with the LHA (DLo) at the bottom of a right-hand page and declination (L_2) such that the respondents lie above the C/S line, the C/S line has been crossed. Then the distance is 90° plus the tabular altitude and the initial course angle is the supplement of the tabular azimuth angle. Similarly, if the tables are entered with the LHA (DLo) at the top of a right-hand page and the respondents are found below the C/S line, the distance is 90° plus the tabular altitude and the initial course angle is the supplement of the tabular azimuth angle. If the tables are entered with the LHA (DLo) at the bottom of a right-hand page and the name of L_2 is contrary to L_1, the respondents are found in the column for L_1 on the facing page. In this case, the C/S line has been crossed and the distance is 90° plus the tabular altitude, and the initial course angle is the supplement of the tabular azimuth angle.

The tabular azimuth angle, or its supplement, is prefixed N or S for the latitude of the point of departure (L_1) and suffixed E or W depending upon the destination being east or west of the point of departure (DLo).

If all entering arguments are integral degrees, the distance and course angle are obtained directly from the tables without interpolation. If the latitude of the destination is non-integral, interpolation for the additional minutes of latitude is done as in correcting altitude for declination increment. If the latitude of departure (L_1) or difference of longitude (DLo) is non-integral, the additional interpolation is done graphically.

Since the latitude of destination becomes the declination entry, and all declinations appear on every page, the great circle solution can always be extracted from the volume which covers the latitude of the point of departure.

Example 1: (L_1 and L_2 on same side of equator) *-Using Pub. No. 229, Vol 2, find the distance and initial great circle course from lat. 22°S, long. 116°E to lat. 20°S, long. 31°E.*

Solution: *Refer to Figure 1207b. The point of departure (L 22° S, λ 116° E) replaces the AP of the observer; The destination (L 20° S, λ 031° E) replaces the GP of the celestial body; The difference of longitude (DLo 085°) replaces local hour angle (LHA) of the body.*

Enter Pub. No. 229, Volume 2 with L 22° (Same Name), LHA 085°, and declination S 20° (page 172). The respondents fall above the C/S line, and thus correspond to a celestial body above the celestial horizon. Therefore, 90° minus the tabular altitude becomes the distance (90° - 11° 46.5' = 78° 13.5' = 4,693.5 nm); the tabular azimuth angle (Z), here S 073.0° W, becomes the initial great circle course angle, prefixed S for the latitude of the point of departure (L1) and suffixed W due to the destination being west of the point of departure (DLo).

Answer:

D = 4,693.5 nautical miles (nm)

C = S 073.0° W ∴ Cn = 253.0 °T .

Example 2: (L_1 and L_2 on opposite sides of the equator) *- Using Pub. No. 229, Vol 2, find the distance and initial great circle course from lat. 28°N, long. 122°W to lat. 24°S, long. 151°E.*

Solution: *Refer to Figure 1207b. The point of departure (L 28° N, λ 122° W) replaces the AP of the observer; The destination (L 24° S, λ 151° E) replaces the GP of the celestial body; The difference of longitude (DLo 087°) replaces local hour angle (LHA) of the body.*

Enter Pub. No. 229 Volume 2 with L 28° (Contrary Name), LHA 087°, and declination S 24°. To find corresponding entries requires the C/S line be crossed. Thus, the respondents correspond to those of a celestial body below the celestial horizon. Therefore, the tabular altitude plus 90° becomes the distance (08° 33.2' + 90° = 098° 33.2' = 5,913.2 nm); the supplement of tabular azimuth angle (Z) becomes the initial great circle course angle, prefixed N for the latitude of the point of departure (L1) and suffixed W since the destination is west of the point of departure (DLo) (180° - 67.3° = 112.7°). Note that the data is extracted from across the CS Line from the entering argument (LHA 87°), indicating that the corresponding celestial body would be below the celestial horizon.

Answer:

D = 5,913.2 nm

C = N112.7° ∴ Cn = 247.3 ° T.

1208. Great Circle Sailing by Computation

In Figure 1208, 1 is the point of departure, 2 the destination, P the pole nearer 1, l-X-V-2 the great circle through 1 and 2, V the vertex, and X any point on the great circle. The arcs P1, PX, PV, and P2 are the colatitudes of points 1, X, V, and 2, respectively. If 1 and 2 are on opposite sides of the equator, P2 is 90°+ L_2. The length of arc 1-2 is the great circle distance between 1 and 2. Arcs 1-2, P1, and P2 form a spherical triangle. The angle at 1 is the initial great circle course from 1 to 2, that at 2 the supplement of the final great circle course (or the initial course from 2 to 1), and that at P the DLo between 1 and 2.

Great circle sailing by computation usually involves solving for the initial great circle course, the distance, latitude/longitude (and sometimes the distance) of the vertex, and the latitude and longitude of various points (X) on the great circle. The computation for initial course and the distance involves solution of an oblique spherical triangle, and any method of solving such a triangle can be used. If 2 is the geographical position (GP) of a celestial body (the point at which the body is at the zenith), this triangle is solved in celestial navigation, except that 90° - D (the altitude) is desired instead of D. The solution for the vertex and any point X usually involves the solution of right spherical triangles.

There are many formulae appropriate for great circle

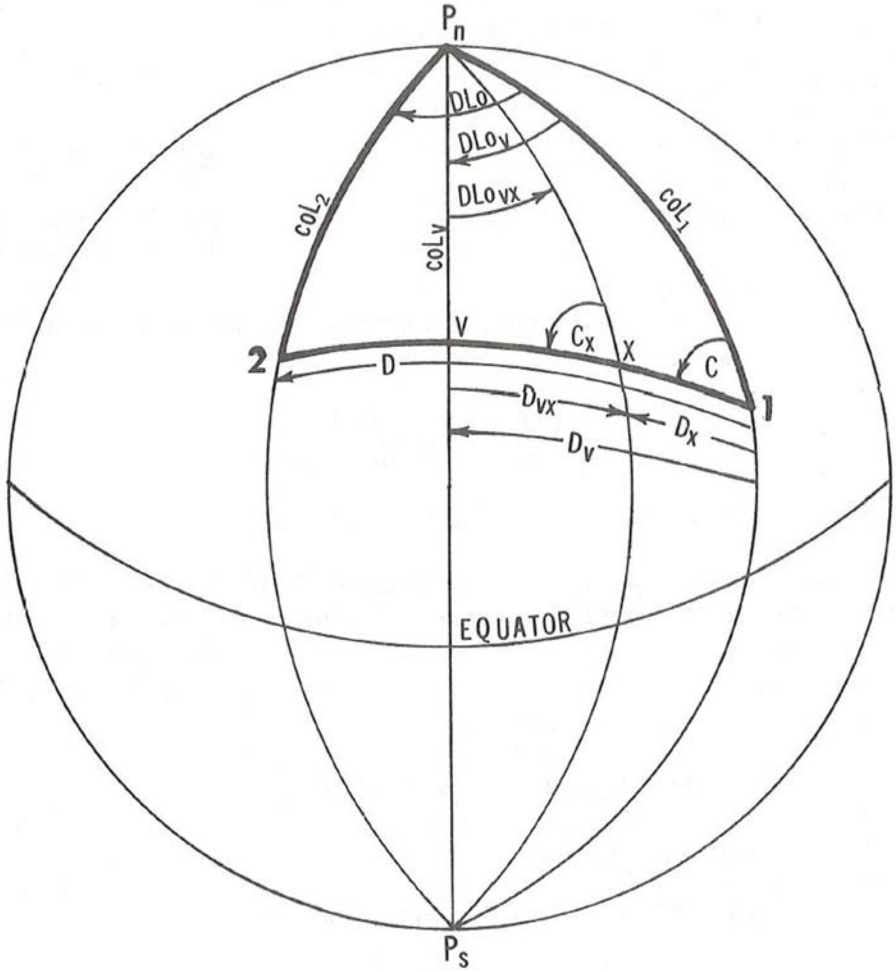


Figure 1208. The navigation triangle of great-circle sailing.

solutions. When solving by computation, angular measurements must be in decimal format to at least three decimal places. Rounding and varying levels of precision will generate differences in results. **Formulae intended for calculator-based solutions are provided below**:

$\cos D = (\sin L_1)(\sin L_2) + (\cos L_1)(\cos L_2)(\cos DLo)$

- If crossing the equator, make L_2 negative

tan Initial Course Angle (C) =

$\tan(C) = \sin DLo / (\cos L_1)(\tan L_2) - (\sin L_1)(\cos DLo)$

- Make L_2 negative if crossing the equator
- If C is negative, add 180°
- Prefix C by L_1 and suffix by DLo

cos Final Course Angle (C) =

$\cos(C) = \sin L_1 - (\cos D)(\sin L_2) / (\sin D)(\cos L_2)$

- Make L_1 negative if crossing the equator
- Label final course angle contrary to L2 and same DLo

Example 1 (L_1 and L_2 on same side of equator): *Using the calculations method, find the distance and initial great circle course from L 22°S, λ 116°E to 20°S, λ 031°E.*

Solution:

DLo = 085°W'ly
cos D = (sin 22°)(sin 20°) + (cos 22°)(cos 20°)(cos 85°)
cos D = 0.204
D = 78.23° = 4,693.8 nm
tan C = (sin 85°) / (cos 22°)(tan 20°) - (sin 22°)(cos 85°)
tan C = 3.2694
∴C = S 72.99° W ≈ S 73° W ∴Cn = 253° *T*

Answer:

D = 4,693.8 nm
Cn = 253° T

Example 2 (L1 and L2 on opposite sides of equator): *Us-*

ing the calculation method, find the distance and initial great circle course from L 28° N, λ 122° W to L 24° S, λ 151° E.

Solution:

DLo = 087° W'ly
$\cos D = (\sin 28°)(\sin -24°) + (\cos 28°)(\cos -24°)(\cos 87°)$
$\cos D = -.1487$
$D = 98.55° = 5{,}913.1$ nm
$\tan C = (\sin 87°) / (\cos 28°)(\tan -24°) - (\sin 28°)(\cos 87°)$
$\tan C = -2.391$
$C = -67.3°$ (if C is negative, subtract from 180°) $\therefore C$ = N 112.7° W $\therefore Cn = 247.3°$ T

Answer:

D = 5,913.1 nm
Cn = 247.3° T

Example 3 (Final Course Angle): *Using the calculation method, find the final course from L 22° S, λ 116° E to L 20° S, λ 031° E. Additional, D = 4,693.8 nm = 78.23°.*

Solution:

cos Final Course Angle (C) = sin L1 - (cos D) (sin L2) / (sin D) (cos L2)
$\cos C = \sin 22° - (\cos 78.23°)(\sin 20°) / (\sin 78.23°)(\cos 20°) = .2988$
$\therefore C$ = N 72.6° W $\therefore Cn = 287.4°$ T

Answer:

Cn = 287.4° T

1209. Points Along the Great Circle

Since the great circle is continuously changing direction as one proceeds along it, no attempt is usually made to follow it exactly. Instead, a number of points along the route are selected (either at specific distances, arc, or DLo from the vertex) and rhumb lines are followed between these selected points. Since for short distances a great circle and a rhumb line almost coincide, this practice effectively yields the savings of the great circle route. This is normally done on a great circle chart. Points can also be determined by formulae or the sight reduction tables. In most cases, the position of the vertex must be known.

Keep in mind that DLo_v and D_v of the closest vertex are never more than 90°. When L_1 and L_2 are on opposite sides of the equator, the farther vertex, 180° away, may be the better vertex to use in the solution for points along the great circle track if it is nearer the mid-point of the route. Navigators may decide to select points along the great circle track by either selecting **equal distances** or **equal DLo** measures from the vertex.

1. Select **equal DLo** intervals each side of the vertex, and solve for the corresponding latitudes. This method provides for shorter legs in higher latitudes and longer legs in lower latitudes. If DLo_v is less than 90°, L_x has the same name as Lv. If DLo_{vx} is greater than 90°, then L_x is of contrary name. Since the great circle is a symmetrical curve about the vertex, any DLo can be applied to λ_v in both directions (E and W) to find two points of equal latitude. However, if whole degrees of λ_x are desired, different E and W intervals are needed unless λ_v is a whole degree or exact half degree. The formula for the DLo technique is:

$$\tan L_x = (\cos DLo_{vx})(\tan L_v).$$

2. Select **equal distances** from the vertex and solve for corresponding positions along the great circle route. In these formulae, distance must be expressed as degrees. If distance is greater than 90° (5,400 nm), L_x is of contrary name to L_v, and DLo_{vx} is greater than 90°. The formulae for the equal distance technique are:

$$\sin L_x = (\sin L_v)(\cos D_{vx})$$
$$\sin DLo_{vx} = (\sin D_{vx}) / (\cos L_x).$$

Example 1*: Determine points along the great circle track 12° on either side of the vertex, with Lv 41° 21.2' N, λ_v 160° 34.4' W.*

Solution:

$\tan L_x = (\cos DLo_{vxSolution})(\tan L_v)$
$\tan L_x = (\cos 12°)(\tan 41.3533°) = (.9781)(.8802) = .8609$

Answer:

$Lx = 40.7252°$
= 40° 43.5' N, λ_x 172° 34.4'W and λ_x 148° 34.4' W

Example 2*: Determine points along the great circle track 300 nm and 600 nm from the vertex, with L_v 41° 21.2' N, λ_v 160° 34.4' W.*

Solution (300 nm):

$\sin L_x = (\sin L_v)(\cos D_{vx})$
$\sin L_x = (\sin 41.3533°)(\cos 5°) = (.6607)(.9962) = .6582$
$\therefore L_x = 41.1627° = 41° 09.8'$ N
$\sin DLo_{vx} = (\sin D_{vx}) / (\cos L_x)$
$\sin DLo_{vx} = (\sin 5°)/(\cos 41.1627°) = (.0872)/(.7528) = .1158$
$\therefore DLo_{vx} = 6.6498° = 6° 38.9'$

Answer:

L_x 41° 09.8' N, λ_x 167° 13.3' W (west of vertex)

and
λ_x 153° 55.5' W (east of vertex).

Solution (600 nm):
$\sin L_x = (\sin 41.3533°)(\cos 10°) = (.6607)(.9848) = .6507$
$\therefore L_x = 40.5944° = 40° 35.7' N$
$\sin DLo_{vx} = (\sin D_{vx}) / (\cos L_x)$
$\sin DLo_{vx} = (\sin 10°) / (\cos 40.5944°)$
$= (.1736) / (.7593) = .2286$
$\therefore DLo_{vx} = 13.2147° = 13° 12.9'$

Answer:
$L_x = 40.5944°$
$= 40° 35.7' N$, *λ_x 173° 47.3' W (west of vertex)*
and
λ_x 147° 21.5' W (east of vertex).

Points along the great circle route may also be determined by using **sight reduction tables**, if the latitude of the point of departure and the initial great circle course angle are integral degrees, points along the great circle are found by entering the sight reduction tables with the latitude of departure as the latitude argument (always Same Name), the initial great circle course angle as the LHA argument, and 90° minus distance to a point on the great circle as the declination argument. The latitude of the point on the great circle and the difference of longitude between that point and the point of departure are the tabular altitude and azimuth angle, respectively. If, however, the respondents are extracted from across the C/S line, the tabular altitude corresponds to a latitude on the side of the equator opposite from that of the point of departure; the tabular azimuth angle is the supplement of the difference of longitude.

Example 1: *Find a number of points along the great circle from L 28° N, λ 125° W when the initial great circle course angle is N 111° W using sight reduction tables.*

Solution: *Entering the tables in Pub. 229 with L 28° (Same Name), LHA 111° (found at the bottom of page 323), and with successive declinations of 85°, 80°, 75°, 40°, etc., the latitudes and differences in longitude from 125°W are found as tabular altitudes and azimuth angles respectively:*

Answer:

D (nm)	300	600	900	3000
D (arc)	5°	10°	15°	50°
Dec.	85°	80°	75°	40°
Hc = Lat.	26° 06.6' N	24° 02.5' N	21° 48.8' N	03° 24.2' N
Dep.	125° W	125° W	125° W	125° W
(Z) = DLo	5.2°	10.2°	15.1°	45.8°
Long.	130.2° W	135.2° W	140.1° W	170.8° W

Table 1209a

Table 1209a

Example 2: *Find a number of points along the great circle track from L 28° N, λ 125° W when the initial great circle course angle (C) is N 069° W using sight reduction tables.*

Solution: *Enter the tables with L 28° (Same Name), LHA 069° (found on page 322), and with successive declinations as shown. Find the latitudes and differences of longitude from 125° W as tabular altitudes and azimuth angles, respectively:*

Answer:

D (nm)	300	600	900	6600
D (arc)	5°	10°	15°	110°
Dec.	85°	80°	75°	20°
Hc = Lat.	29° 41.2' N	31° 09.0' N	32° 22.1' N	27° 15.1' N
Dep.	125° W	125° W	125° W	125° W
(Z) = DLo	5.4°	10.9°	16.6°	80.7°
Long.	130.4° W	135.9° W	141.6° W	154.3° W

Table 1209b

Example 3*: Find a number of points along the great circle from L 28° N, λ 125° W when the initial great circle course angle is N 111° W (Cn = 249° T, which is SW'ly) by calculation. Determine points 5°, 10° and 15° from the point of departure.*

Solution:
First, find the vertex: $\cos L_v = (\cos L_1)(\sin C)$
$\cos L_v = (\cos 28°)(\sin 111°)$
$= (.8829)(.9336) = .8243$
$\therefore L_v = 34.4824° = 34° 29.9' N$
$\sin DLo_v = (\cos C) / (\sin L_v)$
$= (\cos 111°) / (\sin 34.4824) = (-.3584) / (.5662)$
$\sin DLo_v = -.6329 \quad \therefore DLo_v = -39.2644°$ *(E'ly)*
$= 39° 15.9'$ *E'ly*
position of vertex: L 34° 29.9'N, λ 085° 44.1' W
Now find points along the track:
DLo_{vx} *for 5°* $= 130°W - 085.7356° = 44.2644°$
DLo_{vx} *for 10°* $= 135°W - 085.7356° = 49.2644°$
DLo_{vx} *for 15°* $= 140°W - 085.7356° = 54.2644°$
$\tan L_x = (\cos DLo_{vx})(\tan L_v)$

Answer:
$\tan L_{5°} = (\cos 44.2644°) (\tan 34.4824°)$
$= (.7161) (.6868) = .4918$
$\therefore L_{5°} = 26.1879° = 26° 11.3' N$
$\tan L_{10°} = (\cos 49.2644°) (\tan 34.4824°)$
$= (.6526) (.6868) = .4482$
$\therefore L_{10°} = 24.1419° = 24° 08.5' N$
$\tan L_{15°} = (\cos 54.2644°) (\tan 34.4824°)$
$= (.5840) (.6868) = .4011$
$\therefore L_{15°} = 21.8557° = 21° 51.3' N.$

1210. Direction at Various Points Along the Great Circle Track

To determine direction at any point along the great circle route, the following formulae may be used, but unless L_2 is of the same name and equal to or greater than L_1, it leaves doubt as to whether C is less or greater than 90°. The formulae are:

$$\sin C = (\sin DLo) (\cos L_2) / (\sin D), \text{ and}$$
$$\cos C = (\sin L_v) (\sin DLo_v)$$

if the location of the vertex is known.

1211. Finding the Vertex

The vertex will always be equal or greater than L_1 or L_2. If C is less than 90°, the nearer vertex is toward L_2. If C is greater than 90° the vertex is in the opposite direction. Since every great circle circumscribes the entire globe, there is a vertex in each hemisphere. A vertex may be either embedded within the vessel's great circle route, or may be beyond the vessel's intended route and fall either ahead of or behind the intended track. The vertex nearer L_1 has the same name as L_1.

Using *Pub. No. 229* to find the approximate position of the vertex of a great circle track provides a rapid check on the solution by computation. This approximate solution is also useful for voyage planning purposes.

Using the procedures for finding points along the great circle, inspect the column of data for the latitude of the point of departure and find the maximum value of tabular altitude. This maximum tabular altitude and the tabular azimuth angle correspond to the latitude of the vertex and the difference of longitude of the vertex and the point of departure. The vertex can also be calculated (here, C is initial course angle):

Latitude of the vertex

$$\cos L_v = (\cos L1) (\sin C)$$

(name L_v same as L_1)

Difference in λ from departure point to the vertex

$$\sin DLo_{1v} = (\cos C) / (\sin L_v)$$

(If initial course is < 090° vertex is ahead of the vessel and DLo and DLo_v have the same name. If initial course is > 090°, DLo and DLo_v have opposite names and the vertex is behind the vessel).

Distance to the vertex

$$\sin D_v = (\cos L_1) (\sin DLo_v)$$

Longitude when crossing the equator is determined by applying 90° to the longitude of the vertex in the direction of DLo. The longitude of crossing must lie between the points of departure and arrival in the direction of DLo from the vertex.

Example 1: *Find the vertex of the great circle track from lat. 28°N, long. 125°W when the initial great circle course angle (C) is N 069°W.*

Solution: *Enter Pub. No. 229 with L 28° (Same Name), LHA 069° (found on page 322), and inspect the column for L 28° to find the maximum tabular altitude. Maximum altitude (Hc) of 34° 28.9' occurs when declination is 56°. The distance of the vertex from the point of departure can be calculated as 90° - Dec. Thus, 90° - 56° = 34° = 2,040 nm. The corresponding tabular azimuth angle (Z) is 039.3°. Therefore, the difference of longitude between vertex and point of departure is 39.3°.*

Answer:
Distance of the vertex from the point of departure = 2,040 nm
Latitude of vertex = 34° 28.9' N
Longitude of vertex = 125° W + 39.3° W = 164.3° W.

Solution by calculation:
$\cos L_v = (\cos L_1) (\sin C) = (\cos 28°) (\sin 69°)$
$= (.8829) (.9336) = .8243$
$\therefore L_v = 34.4824° = 34° 28.9'N$
$\sin DLo_v = (\cos C) / (\sin L_v)$
$= (\cos 69°) / (\sin 34.4824°)$
$= (.3584) / (.5662) = .6329$
$\therefore DLo_v = 39.2644° = 39° 15.9'$

Answer:
Latitude of vertex = 34° 28.9' N
Longitude of vertex = 125° + 39.2644° = 164° 15.9' W.

1212. Altering a Great Circle Track to Avoid Obstructions

Land, ice, or severe weather, or other operational constraints may prevent the use of great circle sailing for some or all of one's route. One of the principal advantages of the solution by great circle chart is that any hazards become immediately apparent. The pilot charts are particularly useful in this regard. Often a relatively short run by rhumb line is sufficient to reach a point from which the great circle track can be followed. Where a choice is possible, the rhumb line selected should conform as nearly as practicable to the direct great circle.

If the great circle route passes too near a navigational hazard, it may be necessary to follow a great circle to the vicinity of the hazard, one or more rhumb lines along the edge of the hazard, and another great circle to the destination. Another possible solution is the use of composite sailing; still another is the use of two great circles, one from the point of departure to a point near the maximum latitude of unobstructed water and the second from that point to the destination.

1213. Composite Sailing

When the great circle would carry a vessel to a higher latitude than desired, a modification of great circle sailing called **composite sailing** may be used to good advantage. The composite track consists of a great circle from the point of departure and tangent to the limiting parallel, a course line along the parallel, and then a great circle tangent to the limiting parallel and through to the destination.

Solution of composite sailing problems is most easily made with a great circle chart. For this solution, draw lines from the point of departure and the destination, tangent to the limiting parallel. Then measure the coordinates of various selected points along the composite track and transfer them to a Mercator chart, as in great circle sailing.

Composite sailing problems can also be solved by computation, using the equation:

$$\cos DLo_{vx} = \tan L_x \cot L_v$$

The point of departure and the destination are used successively as point X. Solve the two great circles at each end of the limiting parallel, and use parallel sailing along the limiting parallel. Since both great circles have vertices at the same parallel, which is the limiting latitude, computation for C, D, and DLo_{vx} can be made by considering them parts of the same great circle with L_1, L_2, and L_v as given and $DLo = DLo_{v1} + DLo_{v2}$. The total distance is the sum of the great circle and parallel distances.

Example 1: *Determine the longitude at which a limiting latitude of 47° N will be reached when using a composite sailing from L 36° 57.7 N, λ 075° 42.2' W to L 45°-39.1' N, λ 001° 29.8'W. Also determine the longitude when the limiting latitude should be left and the great circle track resumed.*

Solution (for limiting latitude):

L_1 36° 57.7' N = 36.9617°

L_2 45° 39.1' N = 45.6517°

L_v = 47° N

$\cos DLo_{vx} = (\tan L_x) / (\tan L_v)$

$\cos DLo_{v1} = (\tan 36.9617) / (\tan 47)$

$= (.7525) / (1.0724) = .7017$

$\therefore DLo_{v1} = 45.4364° = 45° 26.2'$ E'ly

Answer:

λ_1 = 075° 42.2' W + 45° 26.2' E'ly

= 030° 16.0' W (start rhumb line along L 47° N).

Solution (for λ_2):

$\cos DLo_{v2} = (\tan 45.6517) / (\tan 47)$

$= (1.0230) / (1.0724) = .9539$

$\therefore DLo_{v2} = 17.4651° = 17° 27.9'$ W'ly

Answer:

λ_2 = 001° 29.8' W + 17° 27.9' W'ly

= 018° 57.5' W (end rhumb line along L 47° N).

TRAVERSE TABLES

1214. Using Traverse Tables

Traverse tables can be used in the solution of any of the sailings except great circle and composite. They consist of the tabulation of the solutions of plane right triangles. Because the solutions are for integral values of the course angle and the distance, interpolation for intermediate values may be required. Through appropriate interchanges of the headings of the columns, solutions for other than plane sailing can be made. For the solution of the plane right triangle, any value N in the distance (Dist.) column is the hypotenuse; the value opposite in the difference of latitude (D. Lat.) column is the product of N multiplied by the cosine of the acute angle; and the other number opposite in the departure (Dep.) column is the product of N and the sine of the acute angle. Or, the number in the D. Lat. column is the value of the adjacent side, and the number in the Dep. column is the value of the side opposite the acute angle.

Hence, if the acute angle is the course angle, the adjacent side in the D. Lat. column is meridional difference (m); the opposite side in the Dep. column is DLo. If the acute angle is the mid-latitude of the formula p = DLo cos Lm, then DLo is any value N in the Dist. column, and the departure is the value N (cos L_m) in the D. Lat. column.

The examples below clarify the use of the traverse tables for plane, traverse, parallel, mid-latitude, and Mercator sailings.

1215. Plane Sailing

In plane sailing the figure formed by the meridian through the point of departure, the parallel through the point of arrival, and the course line is considered a plane right triangle. This is illustrated in Figure 1215a. P_1 and P_2 are the points of departure and arrival, respectively. The course angle and the three sides are as labeled. From this triangle:

$$\cos C = \frac{l}{D} \qquad \sin C = \frac{p}{D} \qquad \tan C = \frac{p}{l}.$$

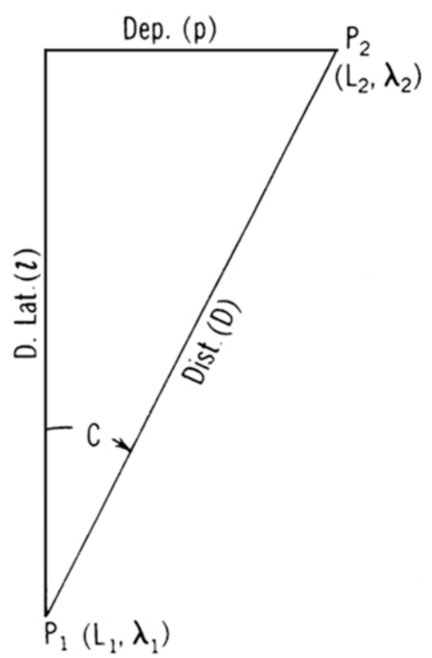


Figure 1215a. The plane sailing triangle.

From the first two of these formulas the following relationships can be derived:

$$l = D \cos C \qquad D = l \sec C \qquad p = D \sin C.$$

Label *l* as N or S, and p as E or W, to aid in identification of the quadrant of the course. Solutions by calculations and traverse tables are illustrated in the following examples:

Example 1: *A vessel steams 188.0 nm on course 005°T.*

Required: *(1) Difference of latitude (l) and departure (p) by computation and (2) Difference of latitude (l) and departure (p) by traverse table.*

(1) - Solution by computation:

Difference of latitude (l) by computation:

$l = D (\cos C)$

$l = 188.0 \text{ nm} (\cos 5°) = 188.0 (.9962) = 187.2856$

$l = 187.3' N$

$l = 3° 07.3' N$

Departure (p) by computation:

$p = D (\sin C)$

$p = 188.0 (\sin 5°) = 188.0 (.0872) = 16.3936$

$p = 16.4 \text{ nm}$

Answer:

$l = 3° 07.3' N$

$p = 16.4 \text{ nm } E$

(2) - Solution by traverse tables: *See* Figure 1215b. *Enter the traverse table and find course 005° at the top of the page. Using the column headings at the top of the table, opposite 188 in the Dist. column extract D. Lat. (l) 187.3 and Dep. (p) 16.4 nm.*

Answer:

$l = 187.3' N = 3° 07.3' N$

$p = 16.4 \text{ nm } E$

Example 2: *A ship has steamed 136.0 nm north and 203.0 nm west.*

Required: *(1) Course and distance by computation and (2) Course and distance by traverse table.*

(1) - Solution by computation:

Course by computation

$\tan C = p / l \;\therefore C = \arctan p / l$

$C = \arctan (203.0/136.0) = \arctan 1.4926$

$C = N\, 56.18° W \quad N\, 56° W$

$C_n \approx 304 °T$

Draw the course vectors to determine the correct course. In this case the vessel has gone north 136 nm and west 203 nm. The course, therefore, is northwesterly and must have been between 270° and 360°.

Distance by computation:

$D = l / (\cos C)$

$D = (136) / (\cos 56.18°)$

$D = (136) / (.5566) = 244.34$

$D = 244.3 \text{ nm}$

TABLE 4

Traverse 5° Table

355° | 005° / 185° | 175°

Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	1.0	0.1	61	60.8	5.3	121	120.5	10.5	181	180.3	15.8	241	240.1	21.0
2	2.0	0.2	62	61.8	5.4	22	121.5	10.6	82	181.3	15.9	42	241.1	21.1
3	3.0	0.3	63	62.8	5.5	23	122.5	10.7	83	182.3	15.9	43	242.1	21.2
4	4.0	0.3	64	63.8	5.6	24	123.5	10.8	84	183.3	16.0	44	243.1	21.3
5	5.0	0.4	65	64.8	5.7	25	124.5	10.9	85	184.3	16.1	45	244.1	21.4
6	6.0	0.5	66	65.7	5.8	26	125.5	11.0	86	185.3	16.2	46	245.1	21.4
7	7.0	0.6	67	66.7	5.8	27	126.5	11.1	87	186.3	16.3	47	246.1	21.5
8	8.0	0.7	68	67.7	5.9	28	127.5	11.2	88	187.3	16.4	48	247.1	21.6
9	9.0	0.8	69	68.7	6.0	29	128.5	11.2	89	188.3	16.5	49	248.1	21.7
10	10.0	0.9	70	69.7	6.1	30	129.5	11.3	90	189.3	16.6	50	249.0	21.8
60	59.8	5.2	20	119.5	10.5	80	179.3	15.7	40	239.1	20.9	300	298.9	26.1
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

275° | 085° / 265° | 095°

85°

Dist.	D. Lat.	Dep.
N.	N x Cos.	N x Sin.
Hypotenuse	Side Adj.	Side Opp.

Figure 1215b. Extract from Table 4.

Answer:
C = 304° T
D = 244.3 nm

(2) - Solution by traverse table: *See* Figure 1215c. *Enter the table and find 136 and 203 beside each other in the columns labeled D. Lat. and Dep., respectively. This occurs most nearly on the page for course angle 56°. Therefore, the course is 304° T. Interpolating for intermediate values, the corresponding number in the Dist. column is 244.3 nm*

TABLE 4

Traverse 34° Table

326° | 034° / 214° | 146°

Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	0.8	0.6	61	50.6	34.1	121	100.3	67.7	181	150.1	101.2	241	199.8	134.8
2	1.7	1.1	62	51.4	34.7	22	101.1	68.2	82	150.9	101.8	42	200.6	135.3
3	2.5	1.7	63	52.2	35.2	23	102.0	68.8	83	151.7	102.3	43	201.5	135.9
4	3.3	2.2	64	53.1	35.8	24	102.8	69.3	84	152.5	102.9	44	202.3	136.4
5	4.1	2.8	65	53.9	36.3	25	103.6	69.9	85	153.4	103.5	45	203.1	137.0
60	49.7	33.6	20	99.5	67.1	80	149.2	100.7	40	199.0	134.2	300	248.7	167.8
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

304° | 056° / 236° | 124°

56°

Dist.	D. Lat.	Dep.
N.	N x Cos.	N x Sin.
Hypotenuse	Side Adj.	Side Opp.

Figure 1215c. Extract from Table 4.

Answer:
C = 304° T
D = 244.3 nm

1216. Traverse Sailing

A **traverse** is a series of courses or a track consisting of a number of course lines, such as might result from a sailing vessel tacking on various courses, or a vessel with operational needs requiring legs of various courses and distances. **Traverse sailing** is the finding of a single equivalent course and distance.

Though the problem can be solved graphically on a chart, traverse tables provide a mathematical solution. The distance to the north or south and to the east or west on each course is tabulated, the algebraic sum of difference of latitude and departure is found, and is then converted to course and distance.

If the effect of an estimated current is to be considered, the set is treated as an additional course, and the drift times the number of hours involved should be used as the distance. If direction and distance from some point, such as a lighthouse, other than the point of departure is desired, the bearing from the selected position to the point of departure is used as the first course and the distance between these points as the first distance.

Example: *A ship steams as follows: course 158°, distance 15.5 nm; course 135°, distance 33.7 nm; course 259°, distance 16.1 nm; course 293°, distance 39.0 nm; course 169°, distance 40.4 nm.*

Required: *Equivalent single (1) course and (2) distance.*

Solution: *Solve each leg as a plane sailing and tabulate each solution as follows: For course 158°, extract the values for D. Lat. and Dep. opposite 155 in the Dist. column. Then, divide the values by 10 and round them off to the nearest tenth. Repeat the procedure for each leg.*

Course	*Dist. (nm)*	*N (nm)*	*S (nm)*	*S (nm)*	*W (nm)*
158°	*15.5*		*14.4*	*5.8*	
135°	*33.7*		*23.8*	*23.8*	
259°	*16.1*		*3.1*		*15.8*
293°	*39.0*	*15.2*			*35.9*
169°	*40.4*		*39.7*	*7.7*	
Subtotals.		*15.2*	*81.0*	*37.3*	*51.7*
			-15.2		*-37.3*
Total			***65.8S***		***14.4W***

Table 1216a

Thus, the latitude difference is S 65.8 nm and the departure is W 14.4 nm. ***Convert this to a course and distance*** *using the formulas discussed for plane sailings, above.*

$l = 65.8\ S$ *and* $p = 14.4\ W$
$\tan C = p / l = 14.4 / 65.8 = .2188$
$\therefore C = S\ 12.3°\ W$
$\therefore C_n = 192.3°\ T$
$D = l / \cos C$
$= 65.8 / \cos 12.3°$
$= 65.8 / .9770 = 67.3\ nm$

Answer:
Cn = 192.3° T
D = 67.3 nm

1217. Parallel Sailing

Parallel sailing consists of the interconversion of departure and difference of longitude. It is the simplest form of spherical sailing and is used when a vessel is sailing due east or west. The formulas for these transformations are:

$$DLo = p \sec L \qquad p = DLo \cos L$$

Example 1: *The DR latitude of a ship on course 090° is 49°30' N. The ship steams on this course until the longitude changes 3°30'.*

Required: *The departure by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:
$DLo = p / (\cos L) \ \therefore p = (DLo)(\cos L)$
$DLo = 3°\ 30' = 210'$
$p = (210')(\cos 49.5°) = 136.4\ nm$

(2) Solution by traverse table: *See* Figure 1217a. *Enter the traverse tables with latitude as course angle and substitute DLo as the heading of the Dist. column and Dep. as the heading of the D. Lat. column. Since the table is computed for integral degrees of course angle (or latitude), the tabulations in the pages for 49° and 50° must be interpolated for the intermediate value (49° 30'). The departure for latitude 49° and DLo 210' is 137.8 nm. The departure for latitude 50° and DLo 210' is 135.0 nm. Interpolating for the intermediate latitude, the departure is 136.4 nm*

Answer:
p = 136.4 nm.

319° | 041° / 221° | 139°							TABLE 4 Traverse 41° Table						319° | 041° / 221° | 139°	
Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
21	15.8	13.8	81	61.1	53.1	141	106.4	92.5	201	151.7	131.9	261	197.0	171.2
22	16.6	14.4	82	61.9	53.8	42	107.2	93.2	02	152.5	132.5	62	197.7	171.9
23	17.4	15.1	83	62.6	54.5	43	107.9	93.8	03	153.2	133.2	63	198.5	172.5
24	18.1	15.7	84	63.4	55.1	44	108.7	94.5	04	154.0	133.8	64	199.2	173.2
25	18.9	16.4	85	64.2	55.8	45	109.4	95.1	05	154.7	134.5	65	200.0	173.9
26	19.6	17.1	86	64.9	56.4	46	110.2	95.8	06	155.5	135.1	66	200.8	174.5
27	20.4	17.7	87	65.7	57.1	47	110.9	96.4	07	156.2	135.8	67	201.5	175.2
28	21.1	18.4	88	66.4	57.7	48	111.7	97.1	08	157.0	136.5	68	202.3	175.8
29	21.9	19.0	89	67.2	58.4	49	112.5	97.8	09	157.7	137.1	69	203.0	176.5
30	22.6	19.7	90	67.9	59.0	50	113.2	98.4	10	158.5	137.8	70	203.8	177.1
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.
311° | 049° / 229° | 131°							49°							

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1217a. Extract from Table 4.

Example 2: *The DR latitude of a ship on course 270° is L 38° 15' S. The ship steams on this course for a distance of 215.5 nm.*

Required: *The change in longitude by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:
p = 215.5'
DLo = (215.5') / (cos 38.25°)
DLo = (215.5') / (0.7853) = 274.4'
DLo = 274.4' W = 4° 34.4' W

Answer:

DLo = 4° 34.4' W

(2) Solution by traverse table: *See* Figure 1217b. *Enter the traverse tables with latitude as course angle and substitute DLo as the heading of the Dist. column and Dep. as the heading of the D. Lat. column. As the table is computed for integral degrees of course angle (or latitude), the tabulations in the pages for 38° and 39° must be interpolated for the minutes of latitude. Corresponding to Dep. 215.5 nm in the former is DLo 273.5', and in the latter DLo 277.3'. Interpolating for minutes of latitude, the DLo is 274.4' W.*

322° | 038° / 218° | 142°							TABLE 4 Traverse 38° Table						322° | 038° / 218° | 142°	
Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
31	24.4	19.1	91	71.7	56.0	151	119.0	93.0	211	166.3	129.9	271	213.6	166.8
32	25.2	19.7	92	72.5	56.6	52	119.8	93.6	12	167.1	130.5	72	214.3	167.5
33	26.0	20.3	93	73.3	57.3	53	120.6	94.2	13	167.8	131.1	73	215.1	168.1
34	26.8	20.9	94	74.1	57.9	54	121.4	94.8	14	168.6	131.8	74	215.9	168.7
35	27.6	21.5	95	74.9	58.5	55	122.1	95.4	15	169.4	132.4	75	216.7	169.3

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1217b. Extracts from Table 4.

321° / 219°	039° / 141°				TABLE 4 Traverse 39° Table							321° / 219°	039° / 141°	
Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
35	27.2	22.0	95	73.8	59.8	55	120.5	97.5	15	167.1	135.3	75	213.7	173.1
36	28.0	22.7	96	74.6	60.4	56	121.2	98.2	16	167.9	135.9	76	214.5	173.7
37	28.8	23.3	97	75.4	61.0	57	122.0	98.8	17	168.6	136.6	77	215.3	174.3
38	29.5	23.9	98	76.2	61.7	58	122.8	99.4	18	169.4	137.2	78	216.0	175.0
39	30.3	24.5	99	76.9	62.3	59	123.6	100.1	19	170.2	137.8	79	216.8	175.6

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1217b. Extracts from Table 4.

Answer:

DLo = 4° 34.4' W

1218. Middle-Latitude Sailing

Middle-latitude sailing combines plane sailing and parallel sailing. Plane sailing is used to find difference of latitude and departure when course and distance are known, or vice versa. Parallel sailing is used to interconvert departure and difference of longitude. The mean latitude (L_m) is normally used for want of a practical means of determining the middle latitude, or the latitude at which the arc length of the parallel separating the meridians passing through two specific points is exactly equal to the departure in proceeding from one point to the other.

The mean latitude (L_m) is half the arithmetic sum of the latitudes of two places on the same side of the equator. It is labeled N or S to indicate its position north or south of the equator. If a course line crosses the equator, solve each course line segment separately.

This sailing, like most elements of navigation, contains certain simplifying approximations which produce answers somewhat less accurate than those yielded by more rigorous solutions. For ordinary purposes, the solutions are more accurate than the navigation of the vessel using them. A correction could be applied to eliminate the error introduced by assuming that the departure and arrival meridians converge uniformly (as the two sides of a plane triangle), rather than as the approximate sine of the latitude. The correction is usually some correction to the middle latitude to obtain a "corrected middle latitude" for use in the solution. Tables for such correction have been published for both spherical and spheroidal earths. However, the actual correction is not a simple function of the middle latitude and DLo, as assumed, because the basic formulae of the sailing are themselves based upon a sphere, rather than a spheroid. Hence, the use of such a correction is misleading, and may introduce more error than it eliminates. The use of any correction is therefore not justified; if highly accurate results are required, a different solution should be used.

The formulae for these transformations are:

$$l = D\,(\cos C) \quad \therefore \cos C = l / D$$
$$p = D\,(\sin C) \quad \therefore \sin C = p / D$$
$$\tan C = p / l$$
$$DLo = p / (\cos Lm) \quad p = (DLo)\,(\cos Lm)$$

The labels (N, S, E, W) of *l*, *p*, and *C* are determined by noting the direction of motion or the relative positions of the two places.

Example 1: *A vessel steams 1,253 nm on course 070° from lat. 15°17.0' N, λ 151°37.0' E.*

Required: *Latitude and longitude of the point of arrival by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:

$D = 1253.0$ nm

$Cn = 070°\,T \therefore C = N\,070°\,E$

$l = (1{,}253.0)\,(\cos 070°) = 428.6' N = 7° 08.6' N$

$p = (1{,}253.0)\,(\sin 070°) = 1{,}177.4$ nm E

$L_1 = 15° 17.0' N$

$\underline{+l = 7° 08.6' N}$

$L_2 = 22° 25.6' N$

$L_m = 18° 51.3' N = 18.855°$

$DLo = p / (\cos Lm) = 1{,}177.4 / \cos 18.855° = 1{,}244.2'$

$DLo = 1{,}244.2' E = 20° 44.2' E$

$\lambda_1 = 151° 37.0' E$

$\underline{+DLo \quad 20° 44.2' E}$

$\lambda_2 = 172° 21.2' E$

Answer:

$L_2 = 22° 25.6' N$

$\lambda_2 = 172° 21.2' E$

(2) Solution by traverse tables: *Refer to Figure 1218a. Enter the traverse table with course 070° and distance 1,253 nm. Because a number as high as 1,253 is not tabulated in the Dist. column, obtain the values for D. Lat. and Dep. for a distance of 125.3 nm and multiply them by 10. Interpolating between the tabular distance arguments yields D. Lat. = 429' and Dep. = 1,178 nm. Converting the D. Lat. value to degrees of latitude yields 7° 09.0'. The point of arrival's latitude, therefore, is 22° 26' N. This results in a mean latitude of 18° 51.5' N.*

Reenter the table with the mean latitude as course angle and substitute DLo as the heading of the Dist. column and Dep. as the heading of the D. Lat. column. Since the table is computed for integral degrees of course angle (or latitude), the tabulations in the pages for 18° and 19° must be interpolated for the minutes of L_m. In the 18° table, interpolate for DLo between the departure values of 117.0 nm and 117.9 nm. This results in a DLo value of 123.9. In the 19° table, interpolate for DLo between the departure values of 117.2 and 118.2. This yields a DLo value of 124.6.

Having obtained the DLo values corresponding to mean latitudes of 18° and 19°, interpolate for the actual value of the mean latitude: 18° 51.5' N. This yields the value of DLo =124.5'. Multiply this final value by ten to obtain DLo = 1,245' = 20° 45' E.

Add the changes in latitude and longitude to the original position's latitude and longitude to obtain the final position.

Answer:
L_2 = 22° 26' N
λ_2 = 172° 22.0' E

Example 2: *A vessel at lat. 8°48.9'S, λ. 89°53.3'W is to proceed to lat. 17°06.9'S, λ 104°51.6'W.*

Required: *Course and distance by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:

$p = DLo\ (\cos L_m)$

$\tan C = p / l$

$D = l / (\cos C)$

The labels (N, S, E, W) of l, p, and C are determined by noting the direction of motion or the relative positions of the two places.

DLo = 14° 58.3' W = 898.3'
L_m *= 12° 57.9' S = 12.965° S*
p = (898.3') (cos 12.965°) = 875.4' = 875.4 nm
L_1 *= 8.815° and* L_2 *= 17.115°*
l = 17.115° - 8.815° = 8.3° = 498'
C = arctan (875.4'/498') = arctan (1.7578) = S 60.4° W
Cn = 240.4° T
D = 498' / (cos 60.4°) = 498' / (.4939) = 1,008.3 nm

Answer:
Cn = 240.4°
D = 1008.2 nm

(2) Solution by traverse tables: *Refer to Figure 1218b. Enter the traverse table with the mean latitude as course angle and substitute DLo as the heading of the Dist. column and Dep. as the heading of the D. Lat. column. Since the table is computed for integral values of course angle (or latitude), it is usually necessary to extract the value of departure for values just less and just greater than the* L_m *and then interpolate for the minutes of Lm. In this case where* L_m *is almost 13°, enter the table with* L_m *13° and DLo 898.3' to find Dep. 875 nm. The departure is found for DLo 89.9', and then multiplied by 10.*

Reenter the table to find the numbers 875 and 498 beside each other in the columns labeled Dep. and D. Lat., respectively. Because these high numbers are not tabulated, divide them by 10, and find 87.5 and 49.8. This occurs most nearly on the page for course angle 60°. Interpolating for intermediate values, the corresponding number in the Dist. column is about 100.5. Multiplying this by 10, the distance is about 1005 nm.

Answer:
C = 240°
D = 1005 nm.

The labels (N, S, E, W) of l, p, DLo, and C are determined by noting the direction of motion or the relative positions of the two places.

1219. Mercator Sailing

Mercator sailing problems can be solved graphically on a Mercator chart. For mathematical solution, the formulas of Mercator sailing are:

$$\tan C = DLo/m \ \therefore DLo = m\ (\tan C)$$

After solving for course angle by Mercator sailing, solve for distance using the plane sailing formula:

$$D = l / (\cos C)$$

The labels (N, S, E, W) of l, p, DLo and C are determined by noting the direction of motion or the relative positions of the two places.

If the true course is near 090° or 270°, a small error in C introduces a large error in DLo. Thus, solving C to the

340° | 020°
200° | 160°

TABLE 4
Traverse **20°** Table

340° | 020°
200° | 160°

Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	0.9	0.3	61	57.3	20.9	121	113.7	41.4	181	170.1	61.9	241	226.5	82.4
2	1.9	0.7	62	58.3	21.2	22	114.6	41.7	82	171.0	62.2	42	227.4	82.8
3	2.8	1.0	63	59.2	21.5	23	115.6	42.1	83	172.0	62.6	43	228.3	83.1
4	3.8	1.4	64	60.1	21.9	24	116.5	42.4	84	172.9	62.9	44	229.3	83.5
5	4.7	1.7	65	61.1	22.2	25	117.5	42.8	85	173.8	63.3	45	230.2	83.8
6	5.6	2.1	66	62.0	22.6	26	118.4	43.1	86	174.8	63.6	46	231.2	84.1
7	6.6	2.4	67	63.0	22.9	27	119.3	43.4	87	175.7	64.0	47	232.1	84.5
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

290° | 070°
250° | 110°

70°

Dist.	D. Lat.	Dep.
N.	N x Cos.	N x Sin.
Hypotenuse	Side Adj.	Side Opp.

342° | 018°
198° | 162°

TABLE 4
Traverse **18°** Table

342° | 018°
198° | 162°

Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	1.0	0.3	61	58.0	18.9	121	115.1	37.4	181	172.1	55.9	241	229.2	74.5
2	1.9	0.6	62	59.0	19.2	22	116.0	37.7	82	173.1	56.2	42	230.2	74.8
3	2.9	0.9	63	59.9	19.5	23	117.0	38.0	83	174.0	56.6	43	231.1	75.1
4	3.8	1.2	64	60.9	19.8	24	117.9	38.3	84	175.0	56.9	44	232.1	75.4
5	4.8	1.5	65	61.8	20.1	25	118.9	38.6	85	175.9	57.2	45	233.0	75.7
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

288° | 072°
252° | 108°

72°

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

341° | 019°
199° | 161°

TABLE 4
Traverse **19°** Table

341° | 019°
199° | 161°

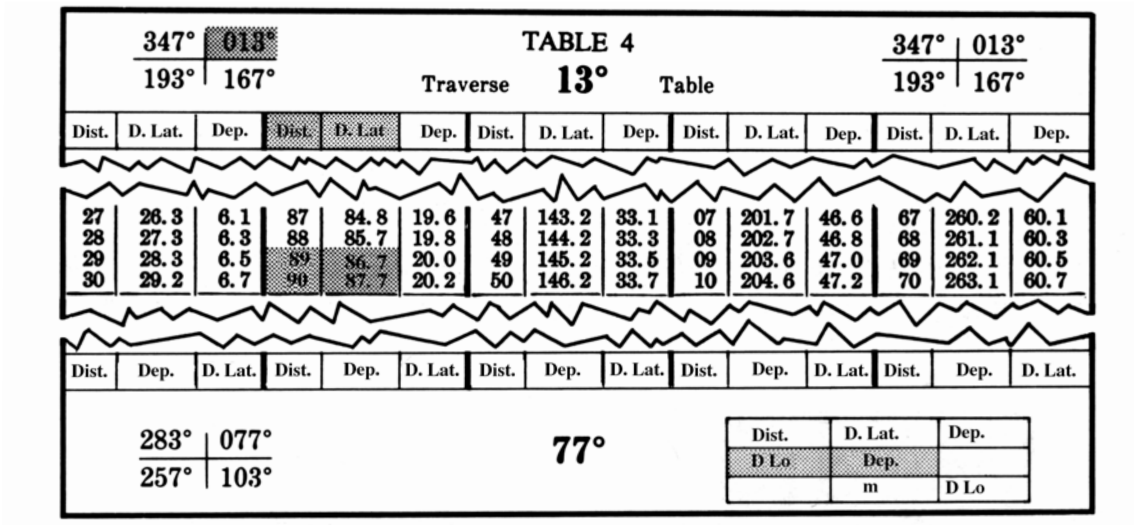
Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	0.9	0.3	61	57.7	19.9	121	114.4	39.4	181	171.1	58.9	241	227.9	78.5
2	1.9	0.7	62	58.6	20.2	22	115.4	39.7	82	172.1	59.3	42	228.8	78.8
3	2.8	1.0	63	59.6	20.5	23	116.3	40.0	83	173.0	59.6	43	229.8	79.1
4	3.8	1.3	64	60.5	20.8	24	117.2	40.4	84	174.0	59.9	44	230.7	79.4
5	4.7	1.6	65	61.5	21.2	25	118.2	40.7	85	174.9	60.2	45	231.7	79.8
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

289° | 071°
251° | 109°

71°

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1218a. Extracts from the Table 4.



347° 013° / 193° 167°					TABLE 4 Traverse 13° Table							347° 013° / 193° 167°		
Dist.	D. Lat.	Dep.	Dist.	D. Lat	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
27	26.3	6.1	87	84.8	19.6	47	143.2	33.1	07	201.7	46.6	67	260.2	60.1
28	27.3	6.3	88	85.7	19.8	48	144.2	33.3	08	202.7	46.8	68	261.1	60.3
29	28.3	6.5	89	86.7	20.0	49	145.2	33.5	09	203.6	47.0	69	262.1	60.5
30	29.2	6.7	90	87.7	20.2	50	146.2	33.7	10	204.6	47.2	70	263.1	60.7
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.
283° 077° / 257° 103°					77°									

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1218b. Extract from Table 4.

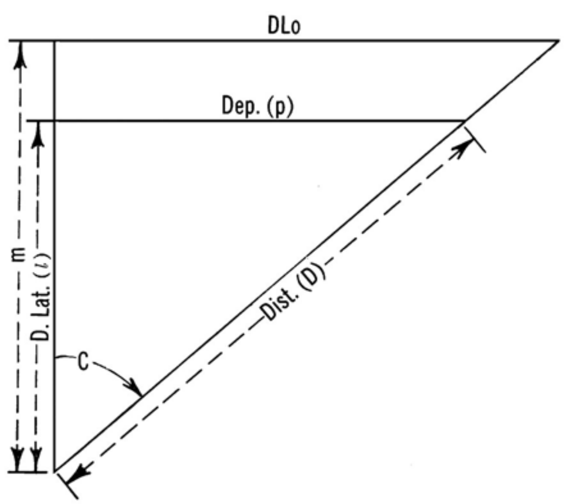


Figure 1219a. Mercator and plane sailing relationship.

nearest 0.1°, as is done by the traverse tables, may introduce a large error in DLo if the true course is near due east or west.

Example 1: *A ship at lat. 32°14.7'N, λ 66°28.9'W is to head for a point near Chesapeake Light, lat. 36°58.7'N, λ 75°42.2'W.*

Required: *Course and distance by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:

$$\tan C = (DLo)/m \therefore DLo = m(\tan C)$$

$$D = l/(\cos C)$$

First calculate the meridional difference by entering Table 6 Meridional Parts and interpolating for the meridional parts for the original and final latitudes. The meridional difference is the difference between these two values. Having calculated the meridional difference, solve for course and distance using the equations above. Figure 1219a depicts the relationship between Mercator and plane sailings.

M_2 (36° 58.7' N) = 2377.1
M_1 (32° 14.7' N) = 2033.4
m = 343.7
λ_2 = 075° 42.2' W
λ_1 = 066° 28.9' W
DLo = 9° 13.3' W = 553.3' W
tan C = DLo / m $\therefore$ C = arctan (DLo / m)
= arctan (553.3'/343.7') = N 58.2° W
$\therefore C_n$ = 301.8° T
L_2 = 36° 58.7' N
L_1 = 32° 14.7' N
l = 4° 44.0' = 284.0'
D = l / (cos C) = 284.0' / (cos 58.2°) = 538.9 nm

Answer:
C = 301.8° T
D = 538.9 nm

(2) Solution by traverse table: *Refer to Figure 1219b. Substitute m as the heading of the D. Lat. column and DLo as the heading of the Dep. column. Inspect the table for the numbers 343.7 and 553.3 in the columns relabeled m and DLo, respectively.Because a number as high as 343.7 is not tabulated in the m column, it is necessary to divide m and DLo by 10. Then inspect to find 34.4 and 55.3 abreast in the*

328° | 032° TABLE 4 328° | 032°

212° | 148° Traverse **32°** Table 212° | 148°

Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
1	0.8	0.5	61	51.7	32.3	121	102.6	64.1	181	153.5	95.9	241	204.4	127.7
2	1.7	1.1	62	52.6	32.9	22	103.5	64.7	82	154.3	96.4	42	205.2	128.2
3	2.5	1.6	63	53.4	33.4	23	104.3	65.2	83	155.2	97.0	43	206.1	128.8
4	3.4	2.1	64	54.3	33.9	24	105.2	65.7	84	156.0	97.5	44	206.9	129.3
5	4.2	2.6	65	55.1	34.4	25	106.0	66.2	85	156.9	98.0	45	207.8	129.8
6	5.1	3.2	66	56.0	35.0	26	106.9	66.8	86	157.7	98.6	46	208.6	130.4
351	297.7	186.0	411	348.5	217.8	471	399.4	249.6	531	450.3	281.4	591	501.2	313.2
52	298.5	186.5	12	349.4	218.3	72	400.3	250.1	32	451.2	281.9	92	502.0	313.7
53	299.4	187.1	13	350.2	218.9	73	401.1	250.7	33	452.0	282.4	93	502.9	314.2
54	300.2	187.6	14	351.1	219.4	74	402.0	251.2	34	452.9	283.0	94	503.7	314.8
55	301.1	188.1	15	351.9	219.9	75	402.8	251.7	35	453.7	283.5	95	504.6	315.3
56	301.9	188.7	16	352.8	220.4	76	403.7	252.2	36	454.6	284.0	96	505.4	315.8
57	302.8	189.2	17	353.6	221.0	77	404.5	252.8	37	455.4	284.6	97	506.3	316.4
58	303.6	189.7	18	354.5	221.5	78	405.4	253.3	38	456.2	285.1	98	507.1	316.9
59	304.4	190.2	19	355.3	222.0	79	406.2	253.8	39	457.1	285.6	99	508.0	317.4
60	305.3	190.8	20	356.2	222.6	80	407.1	254.4	40	457.9	286.2	600	508.8	318.0
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.

302° | 058° **58°**

238° | 122°

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1219b. Extract from Table 4 *composed of parts of left and right hand pages for course angle 58°.*

m and DLo columns, respectively. This occurs most nearly on the page for course angle 58° or course 302°.Reenter the table with course 302° to find Dist. for D. Lat. 284.0'. This distance is 536 miles.

Answer:
Cn = 302° T
D = 536 nm

Example 2: *A ship at lat. 75°31.7' N, λ 79°08.7'W, in Baffin Bay, steams 263.5 nm on course 155°.*

Required: *Latitude and longitude of point of arrival by (1) computation and (2) traverse table.*

Solution:

(1) Solution by computation:
l = D (cos C); and DLo = m (tan C)
D = 263.5 nm
Cn = 155° T ∴C = S 25° E
l = 263.5 (cos 25°) = 238.8' S = 3° 58.8' S
L_1 *75° 31.7' N*
+ l 3° 58.8' S
L_2 *71° 32.9' N*

M_1 *= 7072.4*
M_2 *= 6226.1*
m = 846.3
DLo = 846.3 (tan 25°) = 394.6' E = 6° 34.6'
DLo = 6° 34.6' E
λ_1 *= 079° 08.7' W*
+DLo 6° 34.6' E
λ_2 *= 072° 34.1' W*

Answer:
L_2 *= 71° 32.9' N*
λ_2 *= 072° 34.1' W*

The labels (N, S, E, W) of l, DLo, and C are determined by noting the direction of motion or the relative positions of the two places. Here the vessel is steaming SE'ly.

(2) Solution by traverse table: *Refer to Figure 1219c. Enter the traverse table with course 155° and Dist. 263.5 nm to find D. Lat. 238.8'. The latitude of the point of arrival is found by subtracting the D. Lat. from the latitude of the point of departure. Determine the meridional difference by Table 4 (m = 846.3).*

335° | 025° / 205° | 155°			TABLE 4 Traverse 25° Table									335° | 025° / 205° | 155°		
Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.	Dist.	D. Lat.	Dep.
21	19.0	8.9	81	73.4	34.2	141	127.8	59.6	201	182.2	84.9	261	236.5	110.3
22	19.9	9.3	82	74.3	34.7	42	128.7	60.0	02	183.1	85.4	62	237.5	110.7
23	20.8	9.7	83	75.2	35.1	43	129.6	60.4	03	184.0	85.8	63	238.4	111.1
24	21.8	10.1	84	76.1	35.5	44	130.5	60.9	04	184.9	86.2	64	239.3	111.6
25	22.7	10.6	85	77.0	35.9	45	131.4	61.3	05	185.8	86.6	65	240.2	112.0
33	29.9	13.9	93	84.3	39.3	53	138.7	64.7	13	193.0	90.0	73	247.4	115.4
34	30.8	14.4	94	85.2	39.7	54	139.6	65.1	14	193.9	90.4	74	248.3	115.8
Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.	Dist.	Dep.	D. Lat.
295° | 065° / 245° | 115°						65°								

Dist.	D. Lat.	Dep.
D Lo	Dep.	
	m	D Lo

Figure 1219c. Extract from Table 4.

Reenter the table with course 155° to find the DLo corresponding to m = 846.3. Substitute meridional difference m as the heading of the D. Lat. column and DLo as the heading of the Dep. column. Because a number as high as 846.3 is not tabulated in the m column, divide m by 10 and then inspect the m column for a value of 84.6. Interpolating as necessary, the latter value is opposite DLo 39.4'. The DLo is 394' (39.4' 10). The longitude of the point of arrival is found by applying the DLo to the longitude of the point of departure.

Answer:

L_2 = 71°32.9' N.

λ_2 = 072°34.7' W.

1220. Additional Problems

Example: *A vessel steams 117.3 nm on course 214° T.*
Required: *(1) Difference of latitude, (2) departure, by plane sailing.*

Answers: *(1) l 97.2'S, (2) p 65.6 nm W.*

Example: *A steamer is bound for a port 173.3 nm south and 98.6 nm east of the vessel's position*
Required: *(1) Course, (2) distance, by plane sailing.*

Answers: *(1) C 150.4°; (2) D 199.4 nm by computation, 199.3 nm by traverse table.*

Example: *A ship steams as follows: course 359° T, distance 28.8 nm; course 006°, distance 16.4 miles; course 266° T, distance 4.9 nm; course 144°, distance 3.1 nm; course 333° T, distance 35.8 nm; course 280°, distance 19.3 nm.*
Required: *(1) Course, (2) distance, by traverse sailing.*

Answers: *(1) Cn 334.4° T, (2) D 86.1 nm.*

Example: *The 1530 DR position of a ship is lat. 44°36.3'N, λ 031°18.3'W. The ship is on course 270° T, speed 17 knots.*
Required: *The 2000 DR position, by parallel sailing.*

Answer: *2000 DR: L 44°36.3'N, λ 033°05.7'W.*

Example: *A ship at lat. 33°53.3'S, λ 018°23.1'E, leaving Cape Town, heads for a destination near Ambrose Light, lat. 40°27.1'N, λ 073°49.4'W.*
Required: *(1) Course and (2) distance, by Mercator sailing.*

Answers: *(1) Cn = 310.9° T; (2) D 6,811.5 nm by computation, 6,812.8 mi. by traverse table.*

Example: *A ship at lat. 15°03.7'N, λ 151°26.8'E steams*

57.4 nm on course 035° T.

Required: *(1) Latitude and (2) longitude of the point of arrival, by Mercator sailing.*

Answers: *(1) L 15°50.7'N; (2) λ 152°00.7'E.*