CHAPTER 2

THE MARINE MAGNETIC COMPASS

"Truth lies within a little and certain compass,
but error is immense."

–Henry St. John, Viscount Bolingbroke,
Reflections upon Exile (1716)

INTRODUCTION

This second chapter of the *Advanced Coastal Navigation* (ACN) Course explores the marine compass and its use. The compass is one of the simplest and most useful navigation instruments to be carried aboard a vessel. Arguably, a competent navigator, well-found vessel, up-to-date charts, timepiece, and a good compass are the only real requirements for a safe and efficient voyage. Columbus was able to do this even without good charts or timepieces!

This chapter provides a brief history of the compass, a discussion of the types and parts of the modern compass, an exposition of the principle of operation of the compass, and finally, a discussion of possible compass errors and their measurement so that the mariner can compensate for these errors and steer correct courses. In particular, this chapter reviews so-called TVMDC computations, named for the sequence *True-Variation-Magnetic-Deviation-Compass* that is used to determine compass courses from true courses.

Compass adjustment refers to the process of adjusting small magnets contained in the compass to remove as much error as possible. Many modern textbooks devote considerable space to compass adjustment, and the reader may wonder why this topic is covered only briefly here. The reason is simple. Although compass adjustment is not impossibly complex, it is not trivial and needs to be done right! Professional compass adjusters are available at reasonable cost to perform this service and, unless the mariner is willing to devote a substantial amount of time and intellectual effort, this is a job best left to experts. In addition to adjusting the compass, a professional can provide good advice on the placement of the compass, shipboard electronics, and other gear that may affect the compass. For those who disagree with this assessment and have the time and inclination to master the intricacies of compass adjustment, a brief description is included. Moreover, the references included at the end of this chapter provide a useful starting point for home study.

The material in this chapter is not difficult. But teaching experience indicates that considerable practice is required in order to rapidly and reliably solve the problems discussed in this chapter.

WHAT YOU WILL LEARN IN THIS CHAPTER

- ***The "anatomy" of a compass***
- ***Compass types***
- ***Compass deviation and its measurement***
- ***TVMDC calculations***
- ***Compass errors***

BRIEF HISTORY

The exact origin of the compass is lost in antiquity. Although some accounts claim that the compass was invented well before the birth of Christ (Hewson, 1983), documentary evidence of its use in Europe and China dates back only to approximately 1100 AD (Aczel, 2001; Bowditch, 1995; Collinder, 1955; Jerchow, 1987). (Incidentally, by convention the early Chinese compasses were said to point south, as this was considered a more noble aspect.) The modern compass card (as opposed to needles used on the earliest compasses) apparently originated with Flavio Gioia of Amalfi in southern Italy sometime around 1300 AD (Collinder, 1955), although this is questioned by some (Aczel, 2001).

By the time of Columbus, the compass was well developed and there is evidence (from the diaries of Columbus) that the phenomenon of magnetic variation was at least partially understood. By the early 1700s, charts showing the locations of lines of equal variation *(isogonic lines)* were available. Likewise, compass deviation, an important subject discussed below, was understood in qualitative terms at about this same time, although practical means for compensating for deviation were not developed until 1801 by Captain Matthew Flinders (from which the Flinders bar used in compass adjustment takes its name).

The modern liquid-filled compass, similar to those used on yachts today, dates back to the period 1850 to 1860 when it was developed and patented by E. S. Ritchie of Boston, Massachusetts. (The company founded by Ritchie is still in business today.) Since that time, there have been evolutionary rather than revolutionary developments in the magnetic (mechanical) compass. For example, new lightweight materials are used for compass cards, improved magnets are available, and many other incremental improvements have been made to increase the accuracy, stability, and utility of the magnetic compass.

Elmer Sperry, an American, and Anschutz-Kampfe, a German, during the early part of the 20th century developed the modern gyrocompass, an instrument capable of indicating true rather than magnetic north. Gyroscopes were widely used in naval and merchant ships since the end of World War I. Heretofore, gyroscopes have been electromechanical devices, but laser gyros are now in development that may revolutionize this field. (Gyroscopes are not discussed in this text, as these are not presently available at reasonable cost to the typical boater.)

During the mid-1920s, an electronic compass—termed a fluxgate compass—was developed for aircraft to provide better directional information in turns and during maneuvers. In recent years, this technology has become available at a reasonable cost to the mariner, and for this reason is given passing mention.

The "electronics revolution," a phrase used frequently in this text, also includes directional systems. Outputs from a fluxgate compass can be "processed" by a wide variety of computer systems and used for automated steering (autopilots), and navigational computers (e.g., to compute current set and drift, as discussed in Chapter 7). Yet more sophisticated developments are likely in the near future.

For all these newer developments, the traditional magnetic compass remains one of the most important navigational instruments, as evidenced by the fact that even the most sophisticated ship or aircraft in service today still has at least one magnetic compass aboard. Its relative simplicity, reliability, and lack of dependence on electrical power sources will probably ensure its survival well into the future.

PARTS OF THE COMPASS

Over the years, the marine magnetic compass has evolved into a functional, easy-to-read, convenient, and relatively inexpensive navigational instrument. The damping system of a modern, spherical,

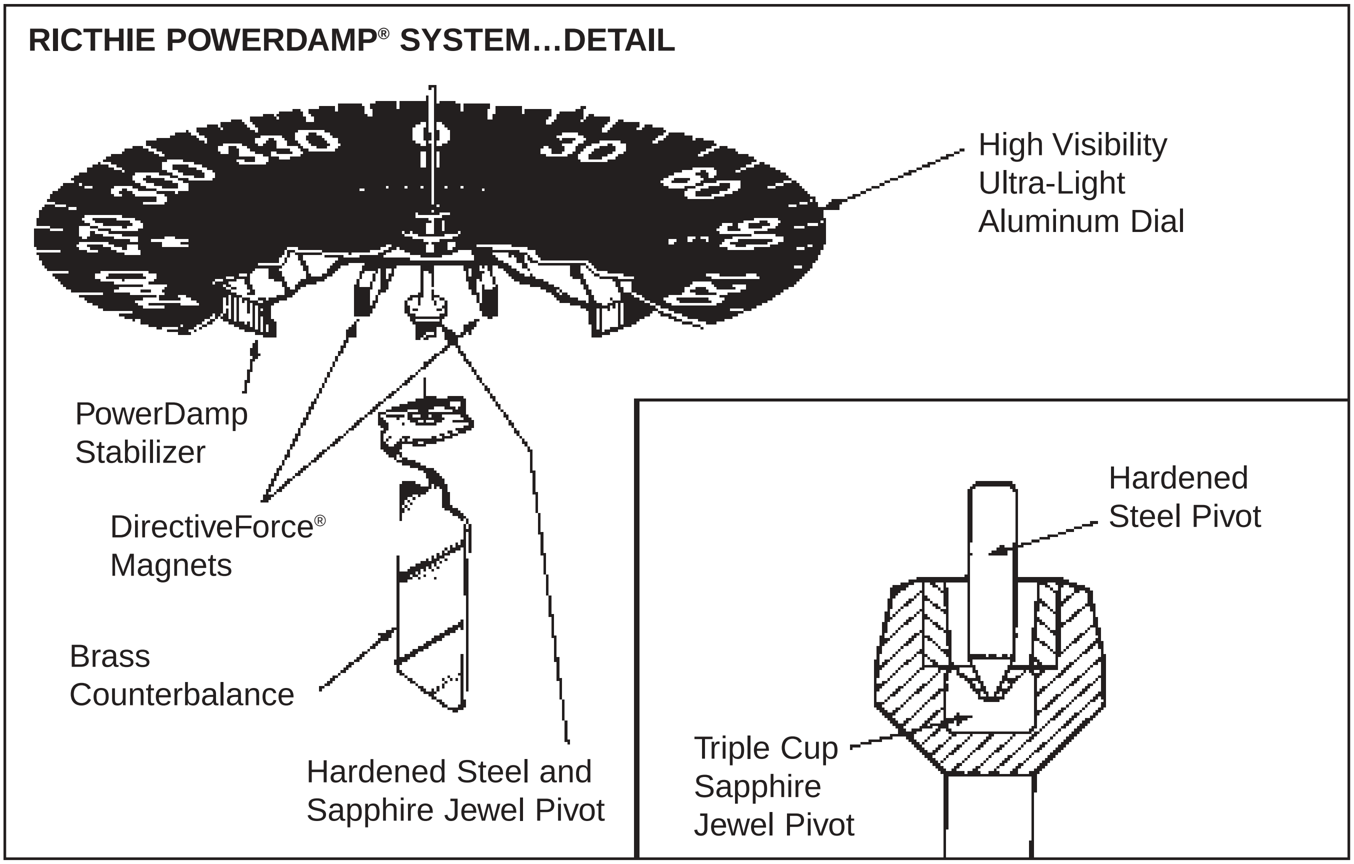

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FIG. 2-1–Damping System of Modern Compass

liquid-filled marine magnetic compass is shown in Figure 2-1. In this compass, a lightweight dial or *compass rose* is graduated in degrees increasing in a clockwise direction from 000 degrees to 359 degrees to indicate the compass heading. The increments shown on the compass dial can be 1 degree, 2 degrees, or, more typically for compasses used on small vessels, 5 degrees. (Studies conducted just prior to World War II indicated that graduations every 5 degrees were significantly easier to read than finer graduations and, in practical terms, nearly as accurate.) Numbers are typically spaced every 30 degrees, and the cardinal points (north, south, east, and west, or abbreviated N, S, E, and W) are also indicated on the dial. Arrows or other marks are sometimes used to designate the intercardinal points (e.g., NE, SE, SW, and NW). Older compasses were traditionally graduated in the mariner's "point" system, mentioned in Chapter 1, in which the circle was divided into 32 compass points, each of 11.25 degrees. These are named, in clockwise order from north: north, north by east, north-northeast, northeast by north, northeast, northeast by east, east-northeast, east by north, east, etc. Naming these points, termed "boxing the compass," was an unpleasant and confusing task used historically in hazing rituals for midshipmen and other would-be mariners. Fortunately, mariners have rediscovered the joy of numbers and the older point system is now only of historical interest. (If you have such a compass, mount it in your den, not on your boat!)

Attached to the dial are the "north-seeking" compass magnets. The dial is supported on a jeweled bearing, which turns on a pivot. In turn, the pivot is mounted in a gimbal system, designed to keep the dial level with the horizon if the vessel pitches or rolls. Fastened to the gimbal is one (or more) *lubber's line*(s). The lubber's line (also termed lubber line [Moody, 1980]) is the index mark against which the dial graduations are read to determine the direction of the vessel rel-

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FIG. 2-2–Combination Front and Top Reading Compass

ative to that of the card. The lubber's line (or principal lubber's line if there are more than one) should be aligned with the fore-and-aft axis of the vessel.

The gimbals, card, and magnets are enclosed in a bowl with a clear, transparent, hemispherical glass (or plastic) top, within which the card and gimbals are free to rotate independently of the attitude of the container. The top (dome) may be impregnated with inhibitors to reduce any discoloration of the card or fluid from ultraviolet radiation and may also magnify the readings, so that the apparent card size is larger. The bowl is filled with a nonfreezing liquid to damp (slow down) the motion of the dial for increased stability and to support much of the weight of the card and the magnets, so as to reduce wear on the pivot. The ultra-lightweight dials in use can be damped with fluids that are not viscous (thick), a combination that provides stability and accuracy without a tendency to "overshoot" and oscillate as the vessel is turned to a new heading. The compass also contains an expansion diaphragm to allow for the expansion and contraction of the damping fluid with temperature or pressure changes. A fill plug is used to replace or "top off" the damping fluid. (It is important that there are no air bubbles in the compass fluid.)

The bowl is supported by a case or holder, generally called a binnacle. Somewhere near the bowl are found the compensating magnets, used to adjust the compass to compensate for the vessel's magnetic environment.

Most compasses are lighted for night use. A low intensity red lamp is preferred to avoid or minimize adverse effects on the night vision of the helmsman or crew. (Incidentally, the wires to the compass light should be twisted to minimize magnetic effects.)

Many compasses come with a hood (adjustable on some models) to reduce glare and improve readability. Removable protective covers are also recommended if the compass is installed in a location where it is exposed to the elements.

COMPASS DIAL DESIGN

There are two principal designs for the compass rose or dial. These are discussed briefly below.

❑ The first design is termed a *top-reading compass* (also a *flat card compass* by some manufacturers). With this design, the mariner reads the heading or bearing "across the card." The lubber's line is located behind the card. The numbers that indicate heading or bearing increase in a clockwise direction—a correct geometric representation. A heading of 030 degrees is to the

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FIG. 2-3–Fluxgate Compass with Digital Readout right of a heading of 000 degrees, for example, and the compass provides the same representation. If the helmsman is asked to turn to 030 degrees from a heading of north, it is clear that this must be a turn to the right. It is also relatively easy to read compass bearings over this compass dial. The compass dial itself is unobstructed through 360 degrees, although its placement aboard the vessel usually limits this range. A top-reading compass is installed forward of the steering mechanism and beneath the helmsman's eye level.

- ❑ The second design is termed a *front-reading compass* (also called a *direct reading compass* by some manufacturers). This compass dial design is typical of most aircraft compasses and is also used for marine compasses. With this design, the lubber's line is in front of the dial and indicates the direction toward which the vessel is heading. However, the dial is graduated in a counterclockwise direction. Thus, for example, the 30-degree graduation on the front-reading dial is located to the left of 000. This apparent reversal in direction is made necessary because the lubber's line is located in front of the dial. The mounting of a front reading compass usually precludes its use for obtaining bearings. This is not a real detriment, since a hand-bearing compass, discussed in Chapter 4, is a ready substitute.

Either design correctly shows the vessel's actual heading, but the front-reading compass design is slightly more confusing and requires a bit more practice before familiarity is assured. An inexperienced helmsman, asked to come to a heading of 030 degrees from north, could glance at the front-reading dial and see that this heading is to the left, and, therefore, begin a turn in the wrong direction before discovering the error. From the perspective of ease of interpretation, the top-reading compass dial is greatly to be preferred. But, it is also important to consider how the compass will be viewed once installed. In the typical powerboat installation (and in sailboats where the compass binnacle is integrated with the wheel), the compass is located on a panel immediately in front of the helmsman, and so a top-reading compass is easy to see. However, in a typical light aircraft the compass is installed at the top of the cockpit (where it is least likely to be affected by magnetic interference from radios or other electronics), at or above the eye level of the pilot, necessitating a front-reading design. Similarly, in certain sailboats the compass is mounted on the outer cabin bulkhead—nearly at eye level for the helmsman seated several feet away—and a front-reading compass is necessary.

Some compass designs, such as that shown in Figure 2-2, combine both types of compass displays in one unit. The model shown in Figure 2-2 shows a front reading dial graduated in 5-degree increments and a top-reading dial that omits a numerical display of degrees. Some compasses also include *inclinometers*, to measure the angle of roll of the vessel.

Yet other compass displays, typically those used with fluxgate compasses, feature a direct digital readout of the heading. Figure 2-3 shows the display unit of a fluxgate compass with digital readouts. Digital readouts are generally shown to the nearest degree, rather than 5 degrees as is common on conventional compasses. Although many prefer digital displays, these also have limitations or disadvantages. (For example, it is impossible to take a bearing on any object that is not aligned with the vessel's heading.) Moreover, the digital display provides less "situational awareness" for the helmsman than does

PHOTO COURTESY OF RITCHIE NAVIGATION

FIG. 2-4–Fluxgate Compass with Digital Readout and Conventional Displays the top-reading compass. This disadvantage can be overcome if the fluxgate compass also incorporates a conventional dial, as is shown in Figure 2-4, which provides precise heading information and situational awareness. The display shown in Figure 2-4 cannot be used to take bearings, however.

Finally, some compasses—called *telltale compasses*—should be mounted in an upside down (overhead mount) position. The telltale compass is usually installed in the ceiling of the navigator's berth, so that the navigator can read the vessel's heading when not on duty. Overhead-mount compasses are a favorite of "single handlers," and can double as a backup compass. (Incidentally, the practice of "single-handing" (voyaging for long distances with only one person aboard) is unsafe, a violation of the navigation rules (a proper lookout cannot be maintained by a sleeping helmsman), and is strongly discouraged.)

Whatever display is chosen, it is important that the numerals on the dial be large and easy to read. Ornate displays, such as were found on older marine compasses, are less readable than the simple, clean designs of today.

BRIEF ADVICE ON COMPASS SELECTION

The best advice on compass selection is not to be miserly. With compasses, as with other items of equipment, you generally get what you pay for. Because the compass is such an important navigational instrument, it is essential that it be of high quality. Incidentally, this comment also applies to small vessels. On average, small vessels are significantly more "lively" than larger vessels. Larger and more expensive compasses have better gimbals and have larger and easier to read dials. The saying "bigger is better" almost always applies to the selection of a compass. Finally, it is recommended that a vessel be equipped with at least two compasses as a precaution against compass failure. A handheld compass (discussed in Chapter 4) can serve as a backup.

PRACTICAL TIP

Carry at least one spare compass aboard—if only a hand-bearing compass. This is cheap insurance. According to Morrison (1942), early mariners carried plenty of spare "needles" (compass needles) aboard. Ferdinand Magellan reportedly had thirty-five spare needles on his ship!

COMPASS MOUNTING

Ideally, the compass should be mounted where it can easily be read, is protected from the elements, and is free of any magnetic influences aboard the vessel (see below). The lubber's line should be precisely aligned with the fore-and-aft axis of the vessel. On larger vessels, these requirements are easy to meet, but this is sometimes more of a problem in smaller craft. Consult a compass adjuster and read the owner's manual (or product literature) for advice on this important topic.

There are several types of compass mounts, each with advantages and disadvantages. Compass mounts include the bracket mount (fast and versatile installation—particularly for angled surfaces), flush mount, deck or binnacle mount, and bulkhead/dash mount.

PRINCIPLE OF OPERATION: DEVIATION

The modem magnetic compass is highly sensitive and is able to align itself with weak magnetic fields, such as the earth's magnetic field. The magnets underneath the compass card will align with the magnetic field and indicate direction relative to this field. But, the magnetic field aboard a ship is actually a combination (resultant) of multiple magnetic fields—that of the earth and those of the vessel and its equipment.

Were the earth's magnetic field acting alone, the compass would indicate direction in the magnetic direction system—that is, the compass would point in the direction of magnetic north. (Please refer again to Chapter 1.) Determination of the direction with respect to true north would involve nothing more than adding or subtracting the local magnetic variation from the indicated compass direction (more below).

However, the magnetic field aboard a vessel is not solely due to the earth's magnetic field. Shipboard electronics, windshield wiper motors, compressed-gas horns,

WARNING

DO NOT PLACE METAL OBJECTS NEAR COMPASS

Do not use the area near the compass as a resting place for metal objects, such as flashlights, cameras, kitchen utensils, certain plotting instruments, and even metal sunglasses. These can affect the accuracy of the compass readings and cause serious course errors!

tachometers, electrical motors, television sets, and other equipment also generate magnetic fields. Indeed, flashlights, camera light meters, tools, and even some kitchen utensils can also affect the compass. (For skeptics, a simple experiment proves this and is highly instructive. For example, note the compass reading, then place a flashlight near the compass and observe how the reading changes.) The vessel itself—particularly steel vessels—may have magnetic fields oriented in a variety of ways. The vessel's magnetic field may even depend upon the direction the vessel was facing when it was constructed or last laid up for the winter (Kielhorn and Klimm, 1978). These additional fields also affect the compass, with the result that the compass heading of the vessel may differ from its magnetic heading. The difference between these is termed deviation. There are actually three "norths" that the mariner need be concerned with: *true north, magnetic north, and compass north. Simply put, deviation is the difference between the direction that the compass actually points and the direction that it would point if there were no local magnetic fields aboard the vessel.* Although statistics on the deviation of uncompensated compasses aboard recreational boats are not available, these deviations could be quite large, say 10 degrees to 15 degrees, and possibly even more.

It is precisely because of the deviation caused by the vessel's magnetic field that correcting magnets are found in all good compasses. A skilled compass adjuster can move the adjusting magnets so as to remove most of the deviation normally caused by the vessel's magnetic field. (A good compass adjuster can also serve as a consultant on compass placement and can advise the mariner how to stow other gear to minimize deviation in the first place.)

Compass Adjustment—A Brief Digression

As noted above, the use of a professional compass adjuster is recommended. This material is added for those interested in a do-it-yourself project. The material in this section is adapted loosely from the former AUXNAV specialty course (COMDTPUB P16798.16A) documentation:

USEFUL TIP

It is important to emphasize that deviation varies with the vessel's heading. When converting a relative bearing to a true or magnetic bearing, novices often make the mistake of applying the deviation appropriate to the relative bearing rather than the vessel's heading. Be careful not to make this error!

- ❑ First, carefully read the directions that come with the vessel's compass and ensure that the compass is mounted in such a way to minimize possible sources of deviation.
- ❑ Second, follow the directions given below to determine the compass deviations on various headings. If these deviations are "acceptable" (a judgement call), then use the "For/Steer" table (see below) directly and do not undertake compass adjustment. If not, then either call a professional compass adjuster or use the following procedure. Read the directions for compass adjustment (contained in the owner's information supplied with the compass) again to ensure that you are thoroughly familiar with the procedure and the location of the two adjusting screws.
- ❑ Third, make the following working tool. Take a sturdy cardboard and a dowel (a pencil will do). Make a hole for the dowel in the center of the cardboard

and draw a straight line across the cardboard through the center. Select a calm, sunny day (with minimal traffic to avoid) for this evolution, in mid-morning or afternoon when the sun will cast a shadow on the dowel. Take the boat out and maintain a constant heading of north as indicated by the compass. Place the dowel in the hole and rotate the board until the shadow of the dowel falls on the line. Now turn the boat in the opposite direction until the shadow falls on the other side of the line. You will have turned 180° (turn and steady on the reciprocal course promptly because the sun moves about 1° in 4 minutes). Read the compass on this heading. Most probably, it will not read *exactly* 180°. Now, use a stainless steel or brass screwdriver on the athwartships (N-S adjustment) adjusting screw; remove half of the difference between the compass reading and 180°. For example, if the compass were to read 170°, use the adjusting screw to set the compass to 175°. Turn back on the original course until the shadow falls on the other side and take out half of the difference between the compass reading and 000°.

❏ Fourth, repeat the process until you can't remove any more error.

❏ Fifth, do the same thing on east-west headings. Head 090° by compass, align the shadow with the line, turn 180°, read the compass, and take out half the error with the other (E-W) adjusting screw. When no further improvements can be made, make another compass deviation card as described below.

For other perspectives, read through appropriate sections of Brogden (1995), Eyges (1989), Denne (1979), and Kaufman (1978) included in the references at the end of this chapter.

It is seldom the case that all the effects of this magnetic field can be compensated for by the adjusting magnets, and usually a small residual deviation (say 2 degrees to 4 degrees, but sometimes more) remains after adjustment. The mariner has two options for dealing with residual deviation. The first is simply to ignore any residual error and effectively compensate for its presence by fixing the vessel's position more often. As a rough rule of thumb, an unrecognized error of 1° means that a vessel would be approximately 1 mile off course (termed *cross-track error*) if it traveled a distance of 60 miles. Table 2-1 shows the cross track error as a function of the distance traveled and the angular error or residual deviation. For short distances, small angular errors are practically insignificant and can sometimes be ignored. However, for longer distances or in conditions of poor visibility (which would prevent detection and identification of landmarks, fixed *aids to navigation* (ATONs), or buoys), simply ignoring deviation cannot be recommended.

The second, and generally preferable, option is to measure the compass deviation, and use this measured value to correct the observed compass heading to a magnetic heading in the same manner as variation is used to "correct" the magnetic heading to a true heading. However, unlike variation, which depends solely on the vessel's *position*, deviation varies with the vessel's *heading*. Therefore, it is necessary to use the deviation appropriate to the vessel's compass heading before it can be used to convert to the correct magnetic heading. Although, theoretically, this deviation could be different for each possible heading, in practice the deviation is determined for each 15-degree or 30-degree heading increment; then these values are interpolated to estimate the deviation on intermediate headings. This process of determining the deviation on various headings is termed *swinging ship* or *swinging the compass* and is discussed below.

SWINGING SHIP

Normally, professional compass adjusters will swing ship as part of their services to compensate the compass and provide a table of deviations to the mariner. In such cases, the mariner will probably wish to spot-check this table periodically to verify its continuing accuracy. However, the procedures (discussed below) are the same whether the entire deviation table is being prepared or individual values are being spot-checked.

In brief, the procedure for swinging ship is to steady on a known compass course and then take bearings on a distant object or range. The vessel is positioned so that the magnetic bearing to the object to be observed is known. The compass bearing is read directly, or converted from a relative bearing obtained using a *pelorus* and compared with the object's known mag-

DISTANCE TRAVELED MILES	ANGULAR ERROR (DEGREES) 1.00	1.50	2.00	2.50	3.00	4.00	5.00	7.50	10.00
1.00	0.02	0.03	0.03	0.04	0.05	0.07	0.09	0.13	0.18
2.00	0.03	0.05	0.07	0.09	0.10	0.14	0.17	0.26	0.35
3.00	0.05	0.08	0.10	0.13	0.16	0.21	0.26	0.39	0.53
4.00	0.07	0.10	0.14	0.17	0.21	0.28	0.35	0.53	0.71
5.00	0.09	0.13	0.17	0.22	0.26	0.35	0.44	0.66	0.88
6.00	0.10	0.16	0.21	0.26	0.31	0.42	0.52	0.79	1.06
7.00	0.12	0.18	0.24	0.31	0.37	0.49	0.61	0.92	1.23
8.00	0.14	0.21	0.28	0.35	0.42	0.56	0.70	1.05	1.41
9.00	0.16	0.24	0.31	0.39	0.47	0.63	0.79	1.18	1.59
10.00	0.17	0.26	0.35	0.44	0.52	0.70	0.87	1.32	1.76
12.50	0.22	0.33	0.44	0.55	0.66	0.87	1.09	1.65	2.20
15.00	0.26	0.39	0.52	0.65	0.79	1.05	1.31	1.97	2.64
17.50	0.31	0.46	0.61	0.76	0.92	1.22	1.53	2.30	3.09
20.00	0.35	0.52	0.70	0.87	1.05	1.40	1.75	2.63	3.53
22.50	0.39	0.59	0.79	0.98	1.18	1.57	1.97	2.96	3.97
25.00	0.44	0.65	0.87	1.09	1.31	1.75	2.19	3.29	4.41
27.50	0.48	0.72	0.96	1.20	1.44	1.92	2.41	3.62	4.85
30.00	0.52	0.79	1.05	1.31	1.57	2.10	2.62	3.95	5.29
35.00	0.61	0.92	1.22	1.53	1.83	2.45	3.06	4.61	6.17
40.00	0.70	1.05	1.40	1.75	2.10	2.80	3.50	5.27	7.05
45.00	0.79	1.18	1.57	1.96	2.36	3.15	3.94	5.92	7.93
50.00	0.87	1.31	1.75	2.18	2.62	3.50	4.37	6.58	8.82
60.00	1.05	1.57	2.10	2.62	3.14	4.20	5.25	7.90	10.58
70.00	1.22	1.83	2.44	3.06	3.67	4.89	6.12	9.22	12.34
80.00	1.40	2.09	2.79	3.49	4.19	5.59	7.00	10.53	14.11
90.00	1.57	2.36	3.14	3.93	4.72	6.29	7.87	11.85	15.87
100.00	1.75	2.62	3.49	4.37	5.24	6.99	8.75	13.17	17.63

TABLE 2-1–Cross-track error as a function of distance traveled and residual deviation or other angular helm error.

netic bearing, and the deviation is calculated. Professional compass adjusters often use the sun for observation, but most mariners are unfamiliar with celestial navigation and elect to use something simpler, such as a prominent object or range. The object(s) selected for observation should be a good distance away (e.g., 6 miles) to minimize parallax error in the calibration. It is important that swinging ship is done when conditions are nearly ideal, in calm waters and in good visibility. The need for good visibility is obvious. The reason why calm waters are preferred is to simplify steadying the vessel on a compass heading

FIG. 2-5–The range formed by the spire in New Bedford and the Butler Flats light bears approximately 310 degrees.

and reading the compass. Experience shows it can take several hours to swing ship, so the exercise should be planned with sufficient time allowance to be completed within the daylight hours.

The procedure for swinging ship depends upon the compass to be examined and the ability to take bearings on objects not directly aligned with the fore-and-aft axis of the vessel. If the compass is graduated to the nearest degree, and designed and located so that an unobstructed view is possible throughout all 360 degrees, then only a compass is necessary. (This is likely to be the case for relatively few boats.) If, as is more common, the compass is graduated only in 5-degree increments or bearings are not easily read throughout 360 degrees, then it is necessary to use a pelorus as well (discussed below).

DIRECT OBSERVATION USING A RANGE

The easiest method for swinging ship, if circumstances permit, is to use a range and read the compass directly. A range consists of two charted objects that can be viewed and aligned from a distance. For example, consider the spire in New Bedford and the Butler Flats Light located south and east of New Bedford shown in the l210-Tr chart and in Figure 2-5. Both of these objects are likely to be prominent and relatively easy to identify. Approaching from the south, these two objects are exactly in line (one behind the other or in range) on a bearing of 310 degrees true from the vessel to the objects. The bearing can be read from the chart as discussed in Chapter 3, but take the answer as given for the present. The variation in this area, read from the nearest compass rose, is approximately 015 degrees west; so the magnetic bearing of this range would be 310 + 015 = 325 magnetic. (See below for a handy rule to remember whether to add or subtract variation.)

Suppose that the vessel were steadied on a compass course of 000 degrees (compass north) while the vessel was somewhere south of the line drawn on the chart. (This

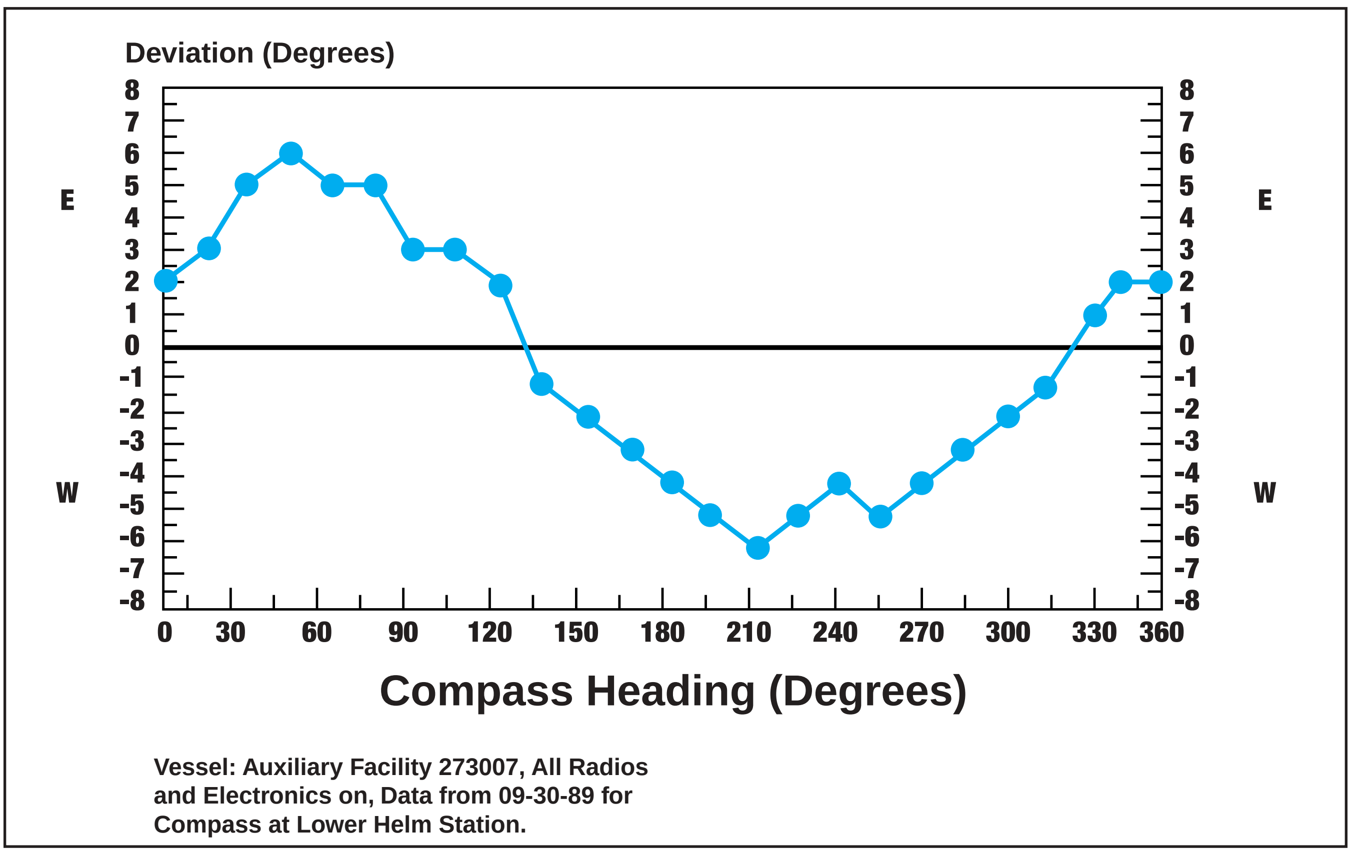

FIG. 2-6–A Plot of Compass Deviations

would, of course, be evident from the vessel because the Butler Flats Light would be to the right of the spire. At the precise instant that the light and the spire appeared to be in line, the magnetic bearing of the range would be 325 degrees from the vessel. At this same instant, suppose that the compass bearing of the range (read over the compass) was 323 degrees (while the compass heading was 000 degrees). The deviation on this heading is the difference between the magnetic bearing, 325 degrees, and the bearing read from the compass, 323 degrees, or 2 degrees. But, is it 2 degrees east, or 2 degrees west? It can, of course, be worked out from first principles (refer to Chapter 1), but it is easy to remember the simple phrase, “compass least, error east.” That is, if the compass bearing is less than the magnetic bearing (as it is in this case, 323 degrees is less than 325 degrees), then the deviation is “east.” (If not, then the error would, of course, be “west.”) Thus, in this example, the estimated compass deviation on a heading of 000 degrees is 002 degrees east. To confirm this result, the process might be repeated and the average deviation noted.

It is convenient to use a worksheet, such as is shown in Table 2-2 to record the observations. This worksheet contains directions as well, which makes it handy to use. The process is now repeated on a compass heading of 015 degrees, 030 degrees, etc., until all observations are recorded.

PLOTTING THE RESULTS

The results should be plotted on a sheet of graph paper to see if there are any “anomalous” results that do not fit the pattern. Overall, the line drawn through the measured deviations should appear as a smooth curve (actually a mixture of trigonometric functions for those technically inclined) free of “bumps” or observations that appear discrepant. Such a curve is drawn in Figure 2-6 and appears generally to confirm the adequacy of the measurements, although the deviations on some headings, such as 240 degrees, should be rechecked. (In Figure 2-6 easterly deviations are shown with a plus sign, and westerly with a minus sign.) Additionally, the deviations on some headings are relatively large (5 or 6 degrees), so the compensation is far from perfect. (A more technical analysis, omitted here, suggests that improved compensation is possible. However, the example is continued for illustrative purposes.)

USE OF A PELORUS

As noted, most marine compass installations do not permit direct reading of compass bearings through a full 360 degrees. Additionally, many compasses are graduated only to 2 degrees or 5 degrees, rather than in 1-degree increments. If either of the statements is true, it is necessary to modify the procedure given above for swinging ship. The most convenient solution is to use a *pelorus,* sometimes called a *dumb compass.*

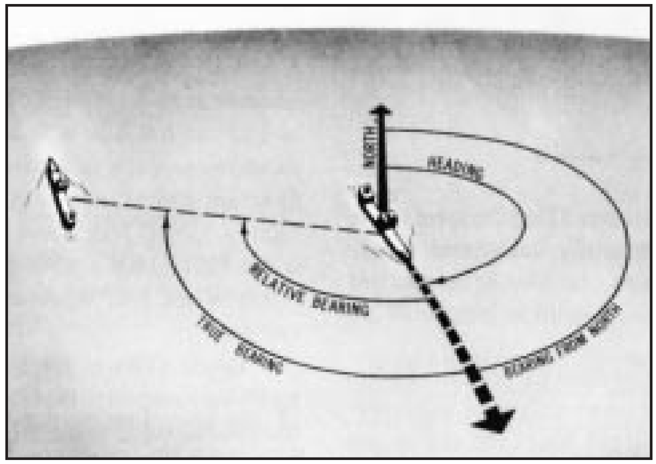

FIG. 2-7–Relative Bearing

A pelorus consists of a graduated compass-like dial (l-degree increments) and sighting vanes that can be rotated around the dial to take bearings. Unlike the “north-seeking” compass dial, however, the position of the dial on the pelorus does not change with the vessel’s heading. The pelorus is mounted and the dial fixed so that the 000-degree mark on the dial is pointed so as to be parallel to the vessel’s bow, precisely aligned with the fore-and-aft axis of the vessel. (Consult the directions supplied with the pelorus for mounting instructions and pay particular attention to the alignment procedure.) The pelorus should be mounted so that the navigator can easily view objects throughout a full 360 degrees.

The bearings read from the pelorus are relative bearings (refer to Chapter 1), rather than compass bearings. For this reason it is necessary to calculate the compass bearing from the simple equation: Ship’s heading + Object’s relative bearing = Object’s compass bearing. Figure 2-7 illustrates this equation.

DATE: *10-15-99* **NAVIGATOR:** *LDM* **VESSEL:** *Altair*
RANGE: *Spire in New Bedford and Butler Flats Light*
NOTES: *Loran, Radar, and VHF Radio ON*

TRUE BEARING OF RANGE: *310* Determined from Nautical Chart or Other Source
VARIATION: *015 West* Determined from Nearby Compass Rose
MAGNETIC BEARING OF RANGE: *325 Magnetic* True +/- Variation, +West, -East

Entry	Vessel's Head Per Compass	Magnetic Direction of Range	Direction of Range Per Compass	Estimated Deviation on This Heading	Notes
1 Where Obtained	2 Read From Lubber's Line Directly	3 Taken From Above Calculation	4 Bearing of Range as Read Over Compass	5 Difference Between Columns 3 and 4 If Column 4< Column 3, Deviation is "East," Otherwise Deviation "West"	This worksheet is designed to be used for determination of deviation where a range is available and can be sighted over the compass. The true bearing of the range can be determined from a nautical chart, *Light List*, or other source. Compass deviation should be determined every 15 degrees of heading, generally starting at 000 degrees. The "notes" section should identify the electronics on board, and operating at the time of the calibration. It is suggested that two tables be prepared, one with all electronics on, and the other with electronics off.
	000	*325*	*323*	*2E*	
	015	*325*	*322*	*3E*	
	030	*325*	*320*	*5E*	
	045	*325*	*319*	*6E*	
	060	*325*	*320*	*5E*	
	075	*325*	*320*	*5E*	

TABLE 2-2–Portion of Worksheet for Determination of Deviations from Range

This extra step requires a slight modification to the worksheet given in Table 2-2 to prepare a compass deviation table. This modified worksheet is shown in Table 2-3. To clarify by example, suppose that a compass deviation table is being prepared using the same range as given in Table 2-2. While on a compass heading of 015 degrees, the navigator sights over the vanes of the pelorus as the range is perfectly aligned. The navigator calls "mark-mark-mark" to allow the helmsman to make slight heading changes to bring the vessel back to the assigned 015-degree heading, and notes the relative bearing, say 307 degrees. Alternatively, the helmsman sings out the vessel's heading on hearing "mark-mark-mark," and the navigator notes this heading. The compass bearing to the range is, therefore, 015 + 307 = 322 degrees (360 degrees will have to be subtracted from this total if the total exceeds 360). The deviation on a compass heading of 015 degrees is, therefore, 3 degrees east as in the earlier example (remember, compass least, error east).

SPOT CHECKS

To spot-check a previously prepared deviation table, all that is necessary is to take advantage of ranges that may appear near the vessel's course. In this case, the helm is put over briefly to align the vessel with the range, the compass heading noted, and the deviation on this heading calculated as discussed above. At a minimum, compass headings should be recorded in a log (see sidebar) for later analysis when the vessel is anchored or docked.

PRACTICAL TIP: USE OF A COMPASS IN REPEATABLE MODE

Get in the habit of entering compass headings in a log on your trips—particularly when in good weather. If the same trip is repeated in conditions of reduced visibility, these same compass headings can be used—even if the compass has not been checked for deviation and errors exist. This use of a navigation instrument is termed its use in repeatable mode. If you return to the same readings of the compass (or other navigation instrument), you compensate for its error. For an interesting discussion of this principle, refer to Brogden (1995).

During a typical voyage there are many opportunities for such spot checks, and these should be used to advantage. Throughout the navies of the world, it is common practice to check the compass at least once daily and to report the results to the captain. For the average boater, it is not necessary to make such frequent or formal checks, but it is appropriate to check deviation at least a few times during the boating season, and whenever a major voyage is planned. Deviation can change whenever new electronic gear is brought aboard (or moved), the vessel is laid up for the winter, or someone inadvertently leaves a flashlight or camera near the compass.

Lightning strikes near the vessel can also affect deviation, and the compass should be checked after electrical storms have passed through the area.

DEVIATION ON INTERMEDIATE HEADINGS

The deviation table consists of entries spaced every 15 degrees or every 30 degrees. Values for intermediate headings are obtained by interpolation. For example, if the deviation were 3 degrees east on a compass heading of 000 degrees and 0 degrees on a heading of 015 degrees, it would be approximately 2 degrees on a heading of 005 degrees. Fancy formulas are not warranted here; simply prorate the deviation directly and round the calculation to the nearest degree.

USE OF THE DEVIATION TABLE

The deviation table is used for two important purposes. First, it is used to calculate the vessel's actual magnetic heading when steering a known compass heading. Second, it is used to calculate the correct compass heading to steer to make good a desired magnetic heading.

The deviation table solves the first objective directly. Refer to Table 2-4, for example, based upon the measurements discussed above.

DATE: *10-15-99* **NAVIGATOR:** *LDM* **VESSEL:** *Altair*
RANGE: *Spire in New Bedford and Butler Flats Light*
NOTES: *Loran, Radar, and VHF Radio ON*

TRUE BEARING OF RANGE: *310* Determined from Nautical Chart or Other Source
VARIATION: *015 West* Determined from Nearby Compass Rose
MAGNETIC BEARING OF RANGE: *325 Magnetic* True +/- Variation (+West, -East)

Entry	**Vessel's Head Per Compass**	**Relative Bearing of Range**	**Direction of Range Per Compass**	**Magnetic Direction of Range**	**Estimated Deviation on This Heading**
1 Where Obtained	2 Read From Lubber's Line Directly	3 Read From Pelorus	4 Vessel's Head (2) Plus Relative Bearing (3) (360° may have to be substracted)	5 Taken From Above Calculation	6 Difference Between Columns 4 and 5 If Column 4< Column 5, Deviation is "East," Otherwise Deviation "West"
	015	*307*	*322*	*325*	*3E*

TABLE 2-3–Portion of Worksheet for Determination of Deviations Using Relative Bearings

COMPASS TO MAGNETIC		MAGNETIC TO COMPASS	
(A) Compass Heading	(B) Deviation	(C) Magnetic Heading	(D) Deviation
000	2E	000	2E
015	3E	015	3E
030	5E	030	4E
045	6E	045	6E
060	5E	060	5E
075	5E	075	5E
090	3E	090	3E
105	3E	105	3E
120	2E	120	1E
135	1W	135	1W
150	2W	150	2W
165	3W	165	2W
180	4W	180	4W
195	5W	195	5W
210	6W	210	6W
225	5W	225	5W
240	4W	240	4W
255	5W	255	5W
270	4W	270	4W
285	3W	285	3W
300	2W	300	2W
315	1W	315	1W
330	1E	330	1E
345	2E	345	2E
360	2E	360	2E

TABLE 2-4–Sample Deviation Table [All Values in Degrees(°)]

Suppose that the vessel's compass heading were 045 degrees. From the first two columns of this table (headed by the phrase "compass to magnetic"), the deviation corresponding to a compass heading of 045 degrees is 6 degrees east. The magnetic heading is the compass heading plus or minus the deviation. Converting from a compass heading to a magnetic heading is often termed "correcting," because this process removes (corrects for) the deviation error. A simple rule to remember is "correcting add east," meaning that in converting from a compass heading to a magnetic heading, easterly deviation is added (westerly deviation is, therefore, subtracted). Using this rule, the corrected or magnetic heading corresponding to a compass heading of 045 would be 045 + 006 = 051 degrees magnetic. Similarly, a compass heading of 030 degrees corresponds to a magnetic heading (refer to Table 2-4) of 035 degrees.

Frequently, however, it is necessary to reverse the process. That is, to find the appropriate compass course to steer to make good a particular magnetic heading. For this task it is necessary to reverse the logic discussed above. For example, suppose that the mariner wants to make good a course of 045 magnetic. What compass course should be steered? From the above discussion, note that on a magnetic heading of 035 degrees the deviation is 5 degrees east, whereas on a magnetic heading of 051 degrees, the deviation is 6 degrees east. A simple interpolation (rounded to the nearest degree) indicates that the deviation on a 045 degree heading is approximately 6 degrees (5 + 10(6-5)/16 = 5.625, rounded to 6). Therefore, the approximate deviation on a magnetic heading of 045 degrees is 6 degrees east, as shown in Table 2-4. When making interpolations, remember that deviations are only measured to the nearest degree. A calculation is only as accurate as the least accurate number, so round all interpolated numbers to the nearest degree.

Continuing the process leads to the results shown in Table 2-4, which completes the deviation table. Use the left half of the table when correcting from compass to magnetic, and the right half when "uncorrecting" from magnetic to compass. (Unless the deviations are quite large, the two halves of the table are virtually identical and, in practice, these differences are often neglected.) Incidentally, the data presented in the *right hand side* (RHS) of Table 2-4 are often used to make a simple "For/Steer" correction card. Entries for this table can be computed as follows. Sup-

NAME	BRIEF DESCRIPTION	REMARKS
Northerly Turning Error	Applies principally when vessel is on northerly or southerly headings and the compass card is tilted with respect to the horizon. Effect is for compass to lag the turn, or momentarily show a turn in the opposite direction when turning from north. In turns from south, the compass leads the turn, i.e., shows the vessel turning more rapidly than it actually is. The effect is greatest in a rapid, steeply banked turn.	Of principal concern to aircraft, but of relevance to all fast boats. Arises from magnetic dip. Phenomenon described for northern hemisphere only.
Acceleration Error	Also due to dip, this error is greatest on headings of east or west and zero on north or south. If the vessel is accelerated on either of these headings, the compass will indicate an apparent turn to the north. When decelerating, the compass indicates a turn to the south. A memory aid to remember the word "ANDS," for Acceleration – North, Deceleration – South.	Effect greatest with vessels capable of large accelerations, e.g., speed boats. Also seen with aircraft. Often observed when boat butts into head sea, or planes down a swell while on an east or west heading.
Oscillation Error	Though listed as a separate error in some texts, this is actually a combination of the above errors. Results from erratic movements of the compass card caused by rough seas or abrupt helm changes. Helmsman has to "average'' out oscillations mentally for precise steering.	
Heeling Error	Of particular relevance to sailing vessels, this error arises from change in the horizontal component of the induced or permanent magnetic fields at the compass due to rolling or pitching of the ship. To a lesser extent heeling errors may be affected by the angle of plane of a powerboat.	Adjusted for by heeling magnets on some compasses.Adjustment is partially a function of the magnetic latitude of the vessel.

NOTE: See article by Kielhorn for details on some of these errors.

TABLE 2-5–Additional Compass Errors Which Arise if Vessel is not Straight and Level, and at Constant Speed pose that the mariner wishes to follow a magnetic heading of 000. Reference to Table 2-4 shows that on a magnetic heading of 000 the deviation is 2° east. Therefore, the compass heading in this case would be 358. So, for a course of 000 magnetic, the mariner should steer 358. Under the heading "For" is placed the magnetic course 000 and under the heading "Steer" is placed 358. The table is completed to create a For/Steer card that is normally posted next to the compass.

COMPASS CALCULATIONS

Navigators need to become familiar with the calculations necessary for converting from true courses to compass courses, and vice versa. Although these calculations are quite simple, practice is necessary to ensure familiarity. For this reason, the following text and examples are given.

VARIATION AND DEVIATION

Variation is the angular difference between true and magnetic north—see Chapter 1. Variation is a function of the vessel's location on the earth. It can be found on the nautical chart. Deviation is the difference between magnetic north and compass north. It is particular to each vessel and is a function of the heading of the vessel. Although related, these are distinct concepts.

DO NOT CONFUSE THESE TWO TERMS.

It is often necessary to convert from true to compass headings or bearings. As discussed in later chapters, courses are laid out on nautical charts and, typically, measured with respect to true north. But to undertake the voyage, the navigator needs to determine how to convert this true course to a compass course to steer. The overall sequence for this conversion is to start with the true course, add or subtract variation to calculate a magnetic course, and then again add or subtract deviation to calculate a compass course: True, Variation, Magnetic, Deviation, Compass, or as it is sometimes said, TVMDC. In addition to learning the sequence of calculations, it is useful to have a handy rule to remember whether to add or subtract variation and deviation.

Throughout history there have been a series of "salty" mnemonics used to help remember the TVMDC sequence. The current politically correct mnemonic is TeleVision Makes Dull Children; Avoid Watching. Decoded, it reveals the sequence of calculations TVMDC and the reminder (AW) to add west when converting from true to compass. For example, what is the compass heading to steer if the true course is 060, variation is 015 west, and the deviation table is as given in Table 2-4? The answer is calculated as follows:

- ❏ First, start at the true course, 060, and convert it to the magnetic course. Since the variation is west, it is added to the true course. The magnetic course is, therefore, 060 + 015 = 075.
- ❏ Second, from Table 2-4, the deviation corresponding to a magnetic heading of 075 degrees is 5 degrees east. From the simple rule to add west in this sequence, it follows that a 5-degree easterly deviation would be subtracted.
- ❏ Third, from the above steps, the required compass course is 075 - 005 = 070 degrees.

The important points to remember are the sequence of calculations and whether to add or subtract variation and deviation. If all else fails, reference to the nearest compass rose on the nautical chart will enable you to figure out whether to add or subtract variation (or deviation).

Sometimes it is necessary to reverse the process, and convert from compass to true. For example, a bearing on a distant object may be taken from the vessel's compass, and it is necessary to convert this bearing to true, before plotting on a nautical chart. The sequence of calculations is just the opposite of that discussed above, i.e., CDMVT. As well, the sign to apply to east or west variation or deviation is also reversed. That is, east is added, and west is subtracted. Although this is simple enough to remember, some prefer to use the additional memory aid: Can Dead Men Vote Twice? At Elections! The first letters are the memory aid to the sequence: Compass, Deviation, Magnetic, Variation, True, and Add East. (Some aircraft pilots were taught the phrase: Can Ducks Make Vertical Turns?)

To illustrate, suppose that the compass heading of the vessel is 065 degrees and an object is sighted bearing directly ahead per the vessel's compass in an area where the variation is 015 degrees west. What is the true bearing? Assuming that the deviation table is as given in Table 2-4, the deviation on a compass heading of 065 degrees is 5 degrees east and, therefore, the magnetic heading of the vessel is 065 + 005 = 070 degrees (add east). In turn, the true heading is the magnetic heading plus or minus variation. If east is to be added, then west should be subtracted for this calculation, so the true heading is 070 – 015 = 055 true. That's all there is to it. Practice until you are proficient.

PHOTO COURTESY OF KVH INDUSTRIES, INC.

FIG. 2-8–Fluxgate Digital Compass. Both the fluxgate sensor and the *Liquid Crystal Display* (LCD) are enclosed in one watertight unit.

LOCAL MAGNETIC DISTURBANCE

Notes indicating magnetic disturbance are printed in magenta on U. S. charts. Where space permits, these notes are printed in the specific area of local magnetic disturbance. Here are some examples of how these are shown:

LOCAL MAGNETIC DISTURBANCE
Differences from normal variation of as much as 5° have been observed in Gastineau Channel in the vicinity of Lat. 58° 15'.

LOCAL MAGNETIC DISTURBANCE
Differences of 12° or more from normal variation may be expected in X Channel in the vicinity of Z Point.

Where limited by space, the full note is placed elsewhere on the chart and the following reference note shown (in magenta) in the area of the disturbance:

LOCAL MAGNETIC DISTURBANCE
(See Note)
Mariners should exercise particular vigilance when operating in these areas.

ADDITIONAL POINTERS ON THE COMPASS

It is important to remember that compass readings are most accurate only when the vessel is level (as opposed to heeling), traveling at a constant speed, and maintaining a constant course. Otherwise, a series of additional compass errors is introduced, as shown in Table 2-5. It is not a good idea to use compass readings obtained while the vessel is heeling, turning, or accelerating/decelerating. The effects of these errors are to make the compass difficult to read and/or to give erroneous indications. These errors are largest for vessels capable of substantial acceleration (e.g., speedboats), and substantial angles of heel or bank. (Consult the references at the end of this chapter for more details.) Directional gyros or gyrocompasses are less prone to these errors and sometimes favored by mariners for this reason (among others).

LOCAL MAGNETIC DISTURBANCES

In some areas of the world, the measured values of magnetic variation differ from the expected (charted) values by several degrees. The sources of these discrepancies are termed *local magnetic disturbances, local attractions, or magnetic anomalies.* Magnetic disturbance notes identify such areas on U. S. nautical charts where errors are greater than or equal to 2° (3° in Alaska). The note will indicate the location and magnitude of the disturbance. The indicated magnitude should not be considered as the largest possible value that may be encountered. Large disturbances are more frequently encountered in the shallow water areas near landmasses (particularly mountains) than on the ocean. Fortunately, the effect of a local magnetic disturbance typically diminishes rapidly with distance. However, in some locations there are multiple sources of disturbances and the effects may be distributed for many miles. Read the nautical chart carefully to determine if there are areas of local magnetic disturbance located along your proposed route. Exercise extra vigilance when transiting these areas. Do not rely entirely on the compass; steer by reference to landmarks and/or ATONs, if possible, and fix your position frequently. Obviously, you should not attempt to calibrate a compass in an area of known local magnetic disturbance. (Local magnetic disturbances are not a compass error, *per se.* Nonetheless, this magnetic phenomenon does affect the compass and should be noted.)

THE FLUXGATE COMPASS

Finally, any modern discussion of compasses would be incomplete without, at least, a passing mention of the fluxgate compass. The fluxgate compass senses the earth's magnetic field electronically, rather than with magnets. (Readers wishing a more complete discussion should refer to the bibliography.) The fluxgate compass consists of a sensor and a display unit. (The sensor and the display unit may be in the same, or different, units.) If separate from the display unit, the sensor can be located remotely, in an area of the vessel where magnetic disturbances are at a minimum. The display unit is small and can be mounted for optimum visibility. Most modern fluxgate systems are integrated with microprocessors, which can perform many useful functions. The model, pictured in Figure 2-8, automatically compensates for deviation (to within +/- 1 degree, in most cases) by simply making a 360 degree turn with the vessel! Other models can also display headings in either true or magnetic (variation data are stored in the microchip) and can furnish electronic inputs to other navigation systems such as the Global Positioning System (GPS), Loran-C, or radar.

An electronic compass is very convenient. However, it does not eliminate the need for a magnetic compass, because electronics are dependent upon a reliable power supply and are easily damaged in the marine environment.

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