CHAPTER 26

EMERGENCY NAVIGATION

INTRODUCTION

2600. Planning For Emergency Navigation

With a complete set of emergency equipment, emergency navigation differs little from traditional shipboard navigation routine. Increasing reliance on complex electronic systems has changed the perspective of emergency navigation. Today it is more likely that a navigator will suffer failure of electronic devices and be left with little more than a sextant with which to navigate than that he will be forced to navigate a lifeboat. In the event of failure or destruction of electronic systems, navigational equipment and methods may need to be improvised. The officer who regularly navigates by blindly "filling in the blanks" or reading the coordinates from "black boxes" will not be prepared to use basic principles to improvise solutions in an emergency.

For offshore voyaging, the professional navigator must become thoroughly familiar with the theory of celestial navigation. He should be able to identify the most useful stars and know how to solve his sights by any widely used method. He should be able to construct a plotting sheet with a protractor and improvise a sextant. For the navigator prepared with such knowledge the situation is never hopeless. Some method of navigation is *always* available. This was recently proven by a sailor who circumnavigated the earth using no instruments of any kind, not even a compass. Basic knowledge can suffice.

The modern ship's regular navigation gear consists of many complex electronic systems. Though they may posses a limited backup power supply, most depend on an uninterrupted supply of electrical power. The failure of that power due to hostile action, fire, or breakdown can instantly render the unprepared navigator helpless. This discussion is intended to provide the navigator with the information needed to navigate a vessel in the absence of the regular suite of navigation gear. Training and preparation for a navigation emergency are essential. This should consist of regular practice in the techniques discussed herein while the regular navigation routine is in effect, so that confidence in emergency procedures is established.

BASIC TECHNIQUES OF EMERGENCY NAVIGATION

2601. Emergency Navigation Kit

The navigator should assemble a kit containing equipment for emergency navigation. Even with no expectation of danger, it is good practice to have such a kit permanently located in the chart room or on the bridge so that it can be quickly broken out if needed. It can be used on the bridge in the event of destruction or failure of regular navigation systems, or taken to a lifeboat if the "abandon ship" call is made.

If practical, full navigational equipment should be provided in the emergency kit. As many as possible of the items in the following list should be included.

1. A **notebook** or journal suitable for use as a deck log and for performing computations.
2. **Charts and plotting sheets**. A pilot chart is excellent for emergency use. It can be used for plotting and as a source of information on compass variation, shipping lanes, currents, winds, and weather. Charts for both summer and winter seasons should be included. Plotting sheets are useful but not essential if charts are available. Universal plotting sheets may be preferred, particularly if the latitude coverage is large. Include maneuvering boards and graph paper.
3. **Plotting equipment**. Pencils, erasers, a straightedge, protractor or plotter, dividers and compasses, and a knife or pencil sharpener should be included. A ruler is also useful.
4. **Timepiece**. A good watch is needed if longitude is to be determined astronomically. It should be waterproof or kept in a waterproof container which permits reading and winding of the watch if necessary without exposing it to the elements. The optimum timepiece is a quartz crystal chronometer, but any high-quality digital wristwatch will suffice if it is synchronized with the ship's chronometer. A portable radio capable of receiving time signals, together with a good wristwatch, will also suffice.
5. **Sextant**. A marine sextant should be included. If this is impractical, an inexpensive plastic sextant will suf-

fice. Several types are available commercially. The emergency sextant should be used periodically in actual daily navigation so its limitations and capabilities are fully understood. Plastic sextants have been used safely on extensive ocean voyages. Do not hesitate to use them in an emergency.

6. **Almanac**. A current *Nautical Almanac* contains ephemeral data and concise sight reduction tables. Another year's almanac can be used for stars and the sun without serious error by emergency standards. Some form of long-term almanac might be copied or pasted in the notebook.
7. **Tables**. Some form of table will be needed for reducing celestial observations. The *Nautical Almanac* produced by the U. S. Naval Observatory contains detailed procedures for calculator sight reduction and a compact sight reduction table.
8. **Compass**. Each lifeboat must carry a magnetic compass. For shipboard use, make a deviation table for each compass with magnetic material in its normal place. The accuracy of each table should be checked periodically.
9. **Flashlight**. A flashlight is required in each lifeboat. Check the batteries periodically and include extra batteries and bulbs in the kit.
10. **Portable radio**. A transmitting-receiving set approved by the Federal Communications Commission for emergency use can establish communications with rescue authorities. A small portable radio may be used as a radio direction finder or for receiving time signals.
11. An **Emergency Position Indicating Radiobeacon (EPIRB)** is *essential*. When activated, this device emits a signal which will be picked up by the COSPAS/SARSAT satellite system and automatically relayed to a ground station. It is then routed directly to rescue authorities. The location of the distress can be determined very accurately. Depending on the type of EPIRB, the signal may even identify the individual vessel in distress, thus allowing rescuers to determine how many people are in danger, the type of emergency gear they may have, and other facts to aid in the rescue. Because of this system, the navigator must question the wisdom of navigating away from the scene of the distress. It may well be easier for rescue forces to find him if he remains in one place. See Chapter 28, The Global Maritime Distress and Safety System (GMDSS).

2602. Most Probable Position

In the event of failure of primary electronic navigation systems, the navigator may need to establish the **most probable position** (MPP) of the vessel. Usually there is usually little doubt as to the position. The most recent fix updated with a DR position will be adequate. But when conflicting information or information of questionable reliability is received, the navigator must determine an MPP.

When complete positional information is lacking, or when the available information is questionable, the most probable position might be determined from the intersection of a single line of position and a DR, from a line of soundings, from lines of position which are somewhat inconsistent, or from a dead reckoning position with a correction for current or wind. Continue a dead reckoning plot from one fix to another because the DR plot often provides the best estimate of the MPP.

A series of estimated positions may not be consistent because of the continual revision of the estimate as additional information is received. However, it is good practice to plot all MPP's, and sometimes to maintain a separate EP plot based upon the best estimate of track and speed made good over the ground. This could indicate whether the present course is a safe one. See Chapter 23.

2603. Plotting Sheets

If plotting sheets are not available, a Mercator plotting sheet can be constructed through either of two alternative methods based upon a graphical solution of the secant of the latitude, which approximates the expansion of latitude.

First method (Figure 2603a):

Step one. Draw a series of equally spaced vertical lines at any spacing desired. These are the meridians; label them at any desired interval, such as 1', 2', 5', 10', 30', 1°, etc.

Step two. Draw and label a horizontal line through the center of the sheet to represent the parallel of the mid-latitude of the area.

Step three. Through any convenient point, such as the intersection of the central meridian and the parallel of the mid-latitude, draw a line making an angle with the horizontal equal to the mid-latitude. In Figure 2603a this angle is 35°.

Step four. Draw in and label additional parallels. The length of the oblique line between meridians is the perpendicular distance between parallels, as shown by the broken arc. The number of minutes of arc between parallels is the same as that between the meridians.

Step five. Graduate the oblique line into convenient units. If 1' is selected, this scale serves as both a latitude and mile scale. It can also be used as a longitude scale by measuring horizontally from a meridian instead of obliquely along the line.

The meridians may be shown at the desired interval and the

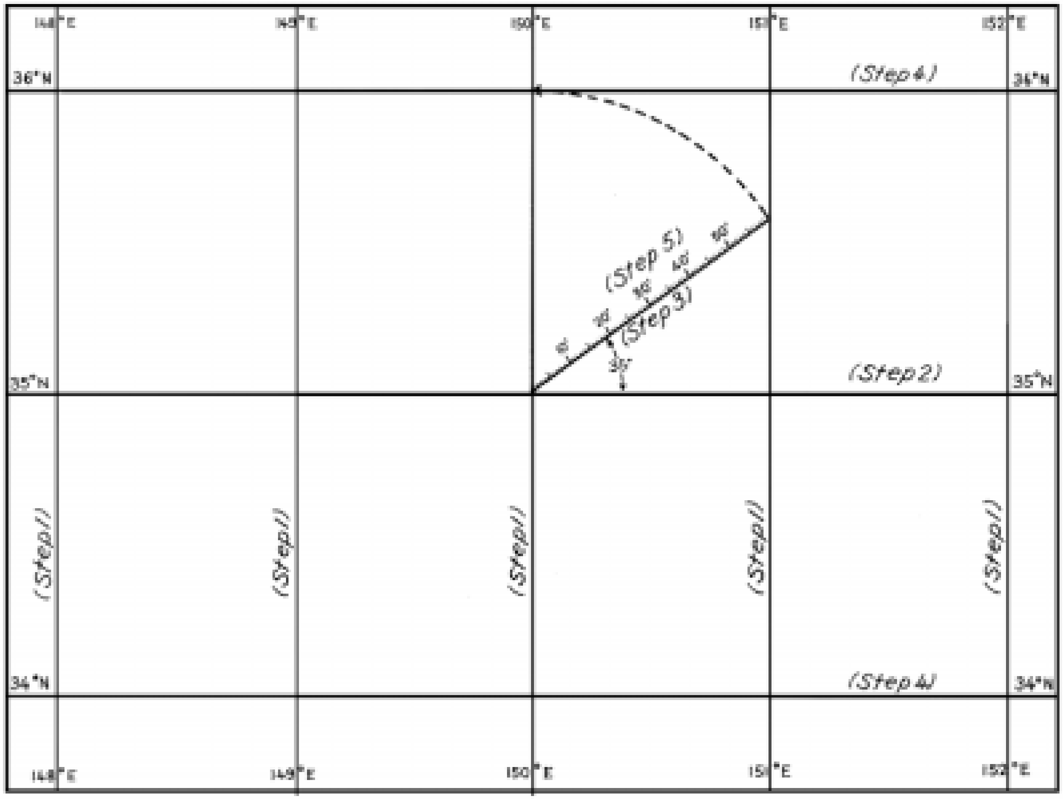

Figure 2603a. Small area plotting sheet with selected longitude scale.

mid-parallel may be printed and graduated in units of longitude. In using the sheet it is necessary only to label the meridians and draw the oblique line. From it determine the interval used to draw in and label additional parallels. If the central meridian is graduated, the oblique line need not be.

Second method (Figure 2603b).

Step one. At the center of the sheet draw a circle with a radius equal to 1° (or any other convenient unit) of latitude at the desired scale. If a sheet with a compass rose is available, as in Figure 2603b, the compass rose can be used as the circle and will prove useful for measuring directions. It need not limit the scale of the chart, as an additional concentric circle can be drawn, and desired graduations extended to it.

Step two. Draw horizontal lines through the center of the circle and tangent at the top and bottom. These are parallels of latitude; label them accordingly, at the selected interval (as every 1°, 30', etc.).

Step three. From the center of the circle draw a line making an angle with the horizontal equal to the mid-latitude. In Figure 2603b this angle is 40°.

Step four. Draw in and label the meridians. The first is a vertical line through the center of the circle. The second is a vertical line through the intersection of the oblique line and the circle. Additional meridians are drawn the same distance apart as the first two.

Step five. Graduate the oblique line into convenient units. If 1' is selected, this scale serves as a latitude and mile scale. It can also be used as a longitude scale by measuring horizontally from a meridian, instead of obliquely along the line.

In the second method, the parallels may be shown at the desired interval, and the central meridian may be printed and graduated in units of latitude. In using the sheet it is necessary only to label the parallels, draw the oblique line, and from it determine the interval and draw in and label additional meridians. If the central meridian is graduated, as shown in Figure 2603b, the oblique line need not be.

The same result is produced by either method. The first method, starting with the selection of the longitude scale, is particularly useful when the longitude limits of the plotting sheet determine the scale. When the latitude coverage is more important, the second method may be preferable. In either method a central compass rose might be printed.

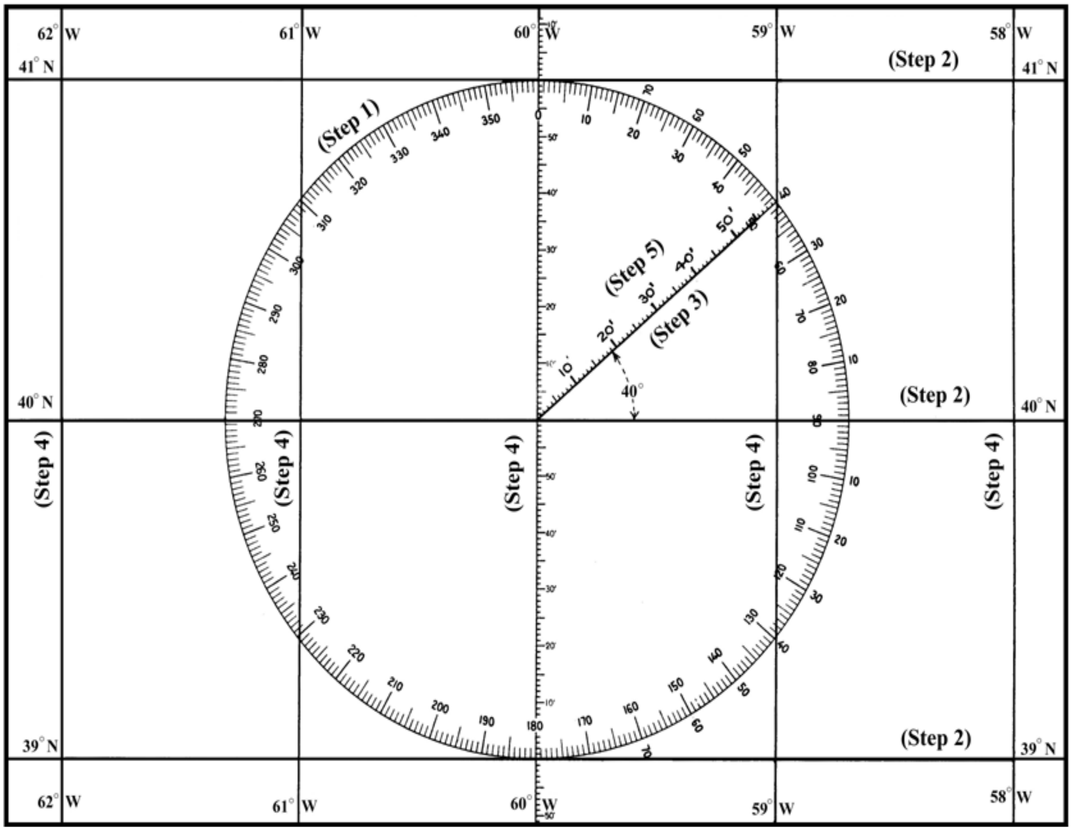

Figure 2603b. Small area plotting sheet with selected latitude scale.

Both methods use a constant relationship of latitude to longitude over the entire sheet and both fail to allow for the ellipticity of the earth. For practical navigation these are not important considerations.

2604. Dead Reckoning

Of the various types of navigation, dead reckoning alone is always available in some form. In an emergency it is of more than average importance. With electronic systems out of service, keep a close check on speed, direction, and distance made good. Carefully evaluate the effects of wind and current. Long voyages with accurate landfalls have been successfully completed by this method alone. This is not meant to minimize the importance of other methods of determining position. However, dead reckoning positions may be more accurate than those determined by other methods. If the means of determining direction and distance (the elements of dead reckoning) are accurate, it may be best to adjust the dead reckoning only after a confirmed fix.

Plotting can be done directly on a pilot chart or plotting sheet. If this proves too difficult, or if an independent check is desired, some form of mathematical reckoning may be useful. Table 2604, a simplified traverse table, can be used for this purpose. This is a critical-type table, various factors being given for limiting values of certain angles. To find the difference or change of latitude in minutes, enter the table with course angle, reckoned from north or south toward the east or west. Multiply the distance run, in miles, by the factor. To find the departure in miles, enter the table with the complement of the course angle. Multiply the distance run in miles by the factor. To convert departure to difference of longitude in minutes, enter the table with mid-latitude and divide the departure by the factor.

Example: *A vessel travels 26 miles on course 205°, from Lat. 41°44'N, Long. 56°21'W.*

Required: *Latitude and longitude of the point of arrival.*

Solution: *The course angle is 205° - 180° = S25°W, and the complement is 90° - 25° = 65°. The factors corresponding to these angles are 0.9 and 0.4, respectively. The difference of*

Angle	0		18		31		41		49		56		63		69		75		81		87		90
Factor		1.0		0.9		0.8		0.7		0.6		0.5		0.4		0.3		0.2		0.1		0.0	

Table 2604. Simplified traverse table.

latitude is 26 × 0.9 = 23' (to the nearest minute) and the departure is 26 × 0.4 = 10 mi. Since the course is in the southwestern quadrant, in the Northern Hemisphere, the latitude of the point of arrival is 41°44' N -23' = 41°21'N. The factor corresponding to the mid-latitude 41°32'N is 0.7. The difference of longitude is 10 ÷ 0.7 = 14'. The longitude of the point of arrival is 56°21'W + 14 = 56°35'W.

Answer: *Lat. 41°21'N, Long. 56°35'W.*

2605. Deck Log

At the beginning of a navigation emergency a navigation log should be started. The date and time of the casualty should be the first entry, followed by navigational information such as ship's position, status of all navigation systems, the decisions made, and the reasons for them.

The best determination of the position of the casualty should be recorded, followed by a full account of courses, distances, positions, winds, currents, and leeway. No important navigational information should be left to memory if it can be recorded.

2606. Direction

Direction is one of the elements of dead reckoning. A deviation table for each compass, including lifeboat compasses, should already have been determined. In the event of destruction or failure of the gyrocompass and bridge magnetic compass, lifeboat compasses can be used.

If an almanac, accurate Greenwich time, and the necessary tables are available, the azimuth of any celestial body can be computed and this value compared with an azimuth measured by the compass. If it is difficult to observe the compass azimuth, select a body dead ahead and note the compass heading. The difference between the computed and observed azimuths is compass error on that heading. This is of more immediate value than deviation, but if the latter is desired, it can be determined by applying variation to the compass error.

Several unique astronomical situations occur, permitting determination of azimuth without computation:

Polaris: Polaris is always within 2° of true north for observers between the equator and latitude 60°N. When this star is directly above or below the celestial pole, its azimuth is exactly north at any latitude. This occurs approximately when the trailing star of either Cassiopeia or the Big Dipper (Alkaid) is directly above or directly below Polaris (Figure 2611). When a line through the trailing stars and Polaris is horizontal, the maximum correction should be applied. Below latitude 50° this can be considered 1°; and between 50° and 65°, 2°. If Cassiopeia is to the right of Polaris, the azimuth is 001° (or 002°), and if to the left, 359° (or 358°). The south celestial pole is located approximately at the intersection of a line through the longer axis of the Southern Cross with a line from the northernmost star of Triangulum Australe perpendicular to the line joining the other two stars of the triangle. No conspicuous star marks this spot (See star charts in Chapter 15).

Meridian transit: Any celestial body bears due north or south at meridian transit, either upper or lower. This is the moment of maximum (or minimum) altitude of the body. However, since the altitude at this time is nearly constant during a considerable change of azimuth, the instant of meridian transit may be difficult to determine. If time and an almanac are available, and the longitude is known, the time of transit can be computed. It can also be graphed as a curve on graph paper and the time of meridian transit determined with sufficient accuracy for emergency purposes.

Body on prime vertical: If any method is available for determining when a body is on the prime vertical (due east or west), the compass azimuth at this time can be observed. Table 20, Meridian Angle and Altitude of a Body on the Prime Vertical Circle provides this information. Any body on the celestial equator (declination 0°) is on the prime vertical at the time of rising or setting. For the sun this occurs at the time of the equinoxes. The star Mintaka (δ Orionis), the leading star of Orion's belt, has a declination of approximately 0.3°S and can be considered on the celestial equator. For an observer near the equator, such a body is always nearly east or west. Because of refraction and dip, the azimuth should be noted when the center of the sun or a star is a little more than one sun diameter (half a degree) above the horizon. The moon should be observed when its upper limb is on the horizon.

Body at rising or setting: Except for the moon, the azimuth angle of a body is almost the same at rising as at setting, except that the former is toward the east and the latter toward the west. If the azimuth is measured both at rising and setting, true south (or north) is midway between the two observed values, and the difference between this value and 180° (or 000°) is the compass error. Thus, if the compass azimuth of a body is 073° at rising, and 277° at setting, true south (180°) is $\frac{073° + 277°}{2} = 175$ by compass, and the compass error is 5°E. This method may be in error if the vessel is moving rapidly in a north or south direction. If the declination and latitude are known, the true azimuth of any body at rising or setting can be determined by means of a diagram on the plane of the celestial meridian or by computation. For this purpose, the body (except the moon) should be considered as rising or setting when its center is a little more than one sun diameter (half a degree) above the horizon, because of refraction and dip.

Finding direction by the relationship of the sun to the hands of a watch is sometimes advocated, but the limitations of this method prevent its practical use at sea.

A simple technique can be used for determining deviation. An object that will float but not drift rapidly before the wind is thrown overboard. The vessel is then steered steadily in the opposite direction to that desired. At a distance of perhaps half a mile, or more if the floating object is still clearly in view, the vessel is turned around in the smallest practical radius, and headed back toward the floating object. The magnetic course is midway between the course toward the object and the reciprocal of the course away from the object. Thus, if the boat is on compass course 151° while heading away from the object, and 337° while returning, the magnetic course is midway between 337° and 151° + 180°

$$= 331°, \text{ or } \frac{337 + 331}{2} = 334° .$$

Since 334° magnetic is the same as 337° by compass, the deviation on this heading is 3°W.

If a compass is not available, any celestial body can be used to steer by, if its diurnal apparent motion is considered. A reasonably straight course can be steered by noting the direction of the wind, the movement of the clouds, the direction of the waves, or by watching the wake of the vessel. The angle between the centerline and the wake is an indication of the amount of leeway.

A body having a declination the same as the latitude of the destination is directly over the destination once each day, when its hour angle equals the longitude, measured westward through 360°. At this time it should be dead ahead if the vessel is following the great circle leading directly to the destination. The *Nautical Almanac* can be inspected to find a body with a suitable declination.

EMERGENCY CELESTIAL NAVIGATION

2607. Almanacs

Almanac information, particularly declination and Greenwich hour angle of bodies, is important to celestial navigation. If the current *Nautical Almanac* is available, there is no problem. If the only copy available is for a previous year, it can be used for the sun, Aries, and stars without serious error, by emergency standards. However, for greater accuracy, proceed as follows:

For declination of the sun, enter the almanac with a time that is earlier than the correct time by $5^h 49^m$ times the number of years between the date of the almanac and the correct date, adding 24 hours for each February 29 that occurs between the dates. If the date is February 29, use March 1 and reduce by one the number of 24 hour periods added. For GHA of the sun or Aries, determine the value for the correct time, adjusting the minutes and tenths of arc to agree with that at the time for which the declination is determined. Since the adjustment never exceeds half a degree, care should be used when the value is near a whole degree, to prevent the value from being in error by 1°.

If no almanac is available, a rough approximation of the declination of the sun can be obtained as follows: Count the days from the given date to the nearer solstice (June 21 or December 22). Divide this by the number of days from that solstice to the equinox (March 21 or September 23), using the equinox that will result in the given date being between it and the solstice. Multiply the result by 90°. Enter Table 2604 with the angle so found and extract the factor. Multiply this by 23.45° to find the declination.

Example 1: *The date is August 24.*

Required: *The approximate declination of the sun.*

Solution: *The number of days from the given date to the nearer solstice (June 21) is 64. There are 94 days between June 21 and September 23. Dividing and multiplying by 90°,*

$$\frac{64}{94} \times 90° = 61.3'$$

The factor from Table 2604 is 0.5. The declination is 23.45° × 0.5 = 11.7°. We know it is north because of the date.

Answer: *Dec. 11.7°N.*

The accuracy of this solution can be improved by considering the factor of Table 2604 as the value for the mid-angle between the two limiting ones (except that 1.00 is correct for 0° and 0.00 is correct for 90°), and interpolating to one additional decimal. In this instance the interpolation would be between 0.50 at 59.5 and 0.40 at 66°. The interpolated value is 0.47, giving a declination of 11.0°N. Still greater accuracy can be obtained by using a table of natural cosines instead of Table 2604. By natural cosine the value is 11.3°N.

If the latitude is known, the declination of any body can be determined by observing a meridian altitude. It is usually best to make a number of observations shortly before and after transit, plot the values on graph paper, letting the ordinate (vertical scale) represent altitude, and the abscissa (horizontal scale) the time. The altitude is found by fairing a curve or drawing an arc of a circle through the points, and taking the highest value. A meridian altitude problem is then solved in reverse.

Example 2: *The latitude of a vessel is 40°16'S. The sun is observed on the meridian, bearing north. The observed altitude is 36°29'.*

Required: *Declination of the sun.*

Solution: *The zenith distance is 90° - 36°29' = 53°31'. The sun is 53°31' north of the observer, or 13°15' north of the equator. Hence, the declination is 13°15' N.*

Answer: *Dec. 13°15' N.*

The GHA of Aries can be determined approximately by considering it equal to GMT (in angular units) on September 23. To find GHA Aries on any other date, add 1° for each day following September 23. The value is approximately 90° on December 22, 180° on March 21, and 270° on June 21. The values so found can be in error by as much as several degrees, and so should not be used if better information is available. An approximate check is provided by the great circle through Polaris, Caph (the leading star of Cassiopeia), and the eastern side of the square of Pegasus. When this great circle coincides with the meridian, LHA ♈ is approximately 0°. The hour angle of a body is equal to its SHA plus the hour angle of Aries.

If an error of up to 4°, or a little more, is acceptable, the GHA of the sun can be considered equal to GMT ± 180° (12^h). For more accurate results, one can make a table of the equation of time from the Nautical Almanac perhaps at five- or ten-day intervals, and include this in the emergency navigation kit. The equation of time is applied according to its sign to GMT ± 180° to find GHA.

2608. Altitude Measurement

With a sextant, altitudes are measured in the usual manner. If in a small boat or lifeboat, it is a good idea to make a number of observations and average both the altitudes and times, or plot on graph paper the altitudes versus time. The rougher the sea, the more important is this process, which tends to average out errors caused by heavy weather observations.

The improvisations which may be made in the absence of a sextant are so varied that in virtually any circumstances a little ingenuity will produce a device to measure altitude. The results obtained with any improvised method will be approximate at best, but if a number of observations are averaged, the accuracy can be improved. A measurement, however approximate, is better than an estimate. Two general types of improvisation are available:

1. Circle. Any circular degree scale, such as a maneuvering board, compass rose, protractor, or plotter can be used to measure altitude or zenith distance directly. This is the principle of the ancient astrolabe. A maneuvering board or compass rose can be mounted on a flat board. A protractor or plotter may be used directly. There are a number of variations of the technique of using such a device. Some of them are:

A peg or nail is placed at the center of the circle. A weight is hung from the 90° graduation, and a string for holding the device is attached at the 270° graduation. When it is held with the weight acting as a plumb bob, the 0° - 180° line is horizontal. In this position the board is turned in azimuth until it is in line with the sun. The intersection of the shadow of the center peg with the arc of the circle indicates the altitude of the center of the sun.

The weight and loop can be omitted and pegs placed at the 0° and 180° points of the circle. While one observer sights along the line of pegs to the horizon, an assistant notes the altitude.

The weight can be attached to the center pin, and the three pins (0°, center, 180°) aligned with the celestial body. The reading is made at the point where the string holding the weight crosses the scale. The reading thus obtained is the zenith distance unless the graduations are labeled to indicate altitude. This method, illustrated in Figure 2608b, is used for bodies other than the sun.

Whatever the technique, reverse the device for half the readings of a series, to minimize errors of construction. Generally, the circle method produces more accurate results

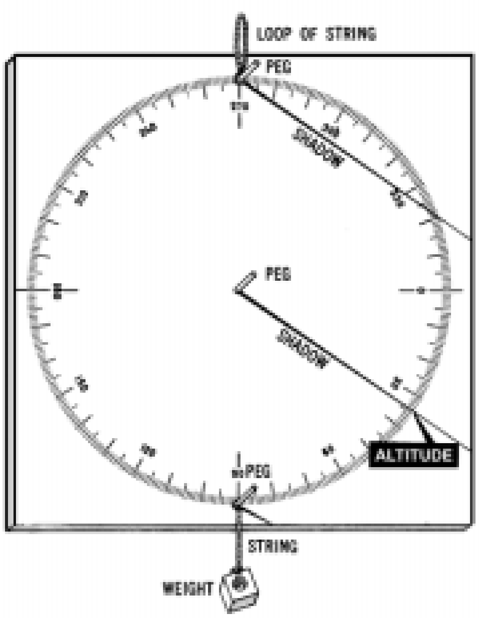

Figure 2608a. Improvised astrolabe; shadow method.

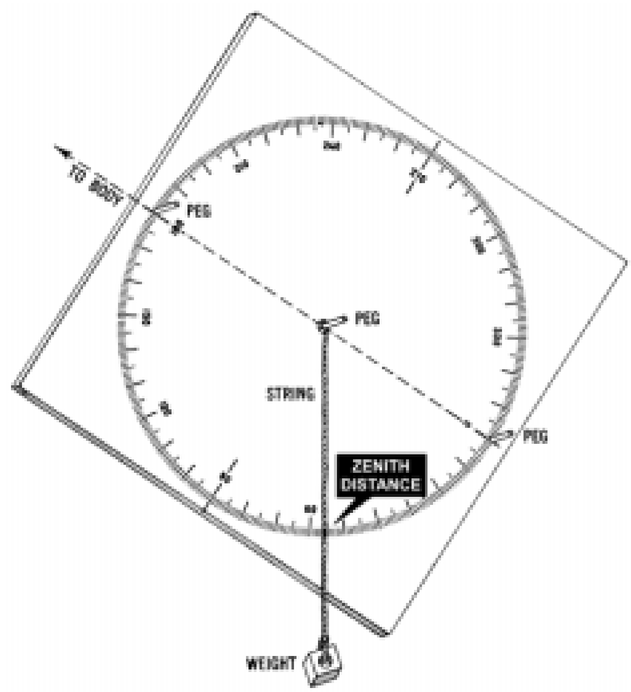

Figure 2608b. Improvised astrolabe; direct sighting method.

than the right triangle method, described below.

2. Right triangle. A cross-staff can be used to establish one or more right triangles, which can be solved by measurement of the angle representing the altitude, either directly or by reconstructing the triangle. Another way of determining the altitude is to measure two of the sides of the triangle and divide one by the other to determine one of the trigonometric functions. This procedure, of course, requires a source of information on the values of trigonometric functions corresponding to various angles. If the cosine is found, Table 2604 can be used. The tabulated factors can be considered correct to one additional decimal for the value midway between the limited values (except that 1.00 is the correct value for 0° and 0.00 is the correct value for 90°) without serious error by emergency standards. Interpolation can then be made between such values.

By either protractor or table, most devices can be graduated in advance so that angles can be read directly. There are many variations of the right triangle method. Some of these are described below.

Two straight pieces of wood can be attached to each other in such a way that the shorter one can be moved along the longer, the two always being perpendicular to each other. The shorter piece is attached at its center. One end of the longer arm is held to the eye. The shorter arm is moved until its top edge is in line with the celestial body, and its bottom edge is in line with the horizon. Thus, two right triangles are formed, each representing half the altitude. For low altitudes, only one of the triangles is used, the long arm being held in line with the horizon. The length of half the short arm, divided by the length of that part of the long arm between the eye and the intersection with the short arm, is the tangent of half the altitude (the whole altitude if only one right triangle is used). The cosine can be found by dividing that part of the long arm between the eye and the intersection with the short arm by the slant distance from the eye to one end of the short arm. Graduations consist of a series of marks along the long arm indicating settings for various angles. The device should be inverted for alternate readings of a series.

A rule or any stick can be held at arm's length. The top of the rule is placed in line with the celestial body being observed, and the top of the thumb is placed in line with the horizon. The rule is held vertically. The length of rule above the thumb, divided by the distance from the eye to the top of the thumb, is the tangent of the angle observed. The cosine can be found by dividing the distance from the eye to the top of the thumb by the distance from the eye to the top of the rule. If the rule is tilted toward the eye until the minimum of rule is used, the distance from the eye to the middle of the rule is substituted for the distance from the eye to the top of the thumb, half the length of the rule above the thumb is used, and the angle found is multiplied by 2. Graduations consist of marks on the rule or stick indicating various altitudes. For the average observer each inch of rule will subtend an angle of about 2.3°, assuming an eye-to-ruler distance of 25 inches. This relationship is good to a maximum altitude of about 20°.

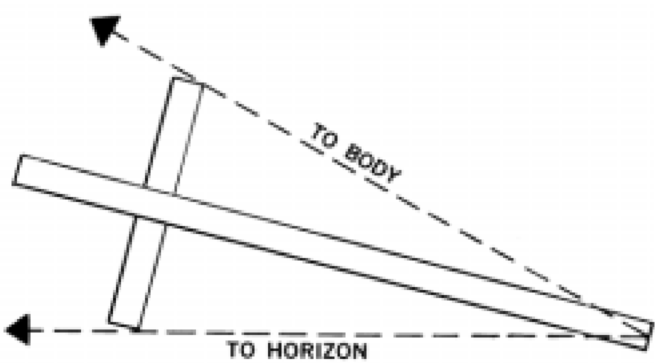

Figure 2608c. Improvised cross-staff.

The accuracy of this relationship can be checked by comparing the measurement against known angles in the sky. Angular distances between stars can be computed by sight reduction methods, including *Pub. No. 229*, by using the declination of one star as the latitude of the assumed position, and the difference between the hour angles (or SHA's) of the two bodies as the local hour angle. The angular distance is the complement of the computed altitude. The angular distances between some well-known star pairs are: end stars of Orion's belt, 2.7°; pointers of the Big Dipper, 5.4°, Rigel to Orion's belt, 9.0°; eastern side of the great square of Pegasus, 14.0°; Dubhe (the pointer nearer Polaris) and Mizar (the second star in the Big Dipper, counting from the end of the handle), 19.3°.

The angle between the lines of sight from each eye is, at arm's length, about 6°. By holding a pencil or finger horizontally, and placing the head on its side, one can estimate an angle of about 6° by closing first one eye and then the other, and noting how much the pencil or finger appears to move in the sky.

The length of the shadow of a peg or nail mounted perpendicular to a horizontal board can be used as one side of an altitude triangle. The other sides are the height of the peg and the slant distance from the top of the peg to the end of the shadow. The height of the peg, divided by the length of the shadow, is the tangent of the altitude of the center of the sun. The length of the shadow, divided by the slant distance, is the cosine. Graduations consist of a series of concentric circles indicating various altitudes, the peg being at the common center. The device is kept horizontal by floating it in a bucket of water. Half the readings of a series are taken with the board turned 180° in azimuth.

Two pegs or nails can be mounted perpendicular to a board, with a weight hung from the one farther from the eye. The board is held vertically and the two pegs aligned with the body being observed. A finger is then placed over the string holding the weight, to keep it in position as the board is turned on its side. A perpendicular line is dropped from the peg nearer the eye, to the string. The body's altitude is the acute angle nearer the eye. For alternate readings of a series, the board should be inverted. Graduations consist of a series of marks indicating the position of the string at various altitudes.

As the altitude decreases, the triangle becomes smaller. At the celestial horizon it becomes a straight line. No instrument is needed to measure the altitude when either the upper or lower limb is tangent to the horizon, as the sextant altitude is then 0°.

2609. Sextant Altitude Corrections

If altitudes are measured by a marine sextant, the usual sextant altitude corrections apply. If the center of the sun or moon is observed, either by sighting at the center or by shadow, the lower-limb corrections should be applied, as usual, and an additional correction of minus 16' applied. If the upper limb is observed, use minus 32'. If a weight is used as a plumb bob, or if the length of a shadow is measured, omit the dip (height of eye) correction.

If an almanac is not available for corrections, each source of error can be corrected separately, as follows:

If a sextant is used, the **index correction** should be determined and applied to all observations, or the sextant adjusted to eliminate index error.

Refraction is given to the nearest minute of arc in Table 2609. The value for a horizon observation is 34'. If the nearest 0.1° is sufficiently accurate, as with an improvised method of observing altitude, a correction of 0.1° should be applied for altitudes between 5° and 18°, and no correction applied for greater altitudes. Refraction applies to all observations, and is always minus.

Dip, in minutes of arc, is approximately equal to the square root of the height of eye, in feet. The dip correction applies to all observations in which the horizon is used as the horizontal reference. It is always a minus. If 0.1° accuracy is acceptable, no dip correction is needed for small boat heights of eye.

The **semidiameter** of the sun and moon is approximately 16' of arc. The correction does not apply to other bodies or to observations of the center of the sun and moon, by whatever method, including shadow. The correction is positive if the lower limb is observed, and negative if the upper limb is observed.

For emergency accuracy, **parallax** is applied to observations of the moon only. An approximate value, in minutes of arc, can be found by multiplying 57' by the factor from Table 2604, entering that table with altitude. For more accurate results, the factors can be considered correct to one additional decimal for the altitude midway between the limiting values (except that 1.00 is correct for 0° and 0.00 is correct for 90°), and the values for other altitudes can be found by interpolation. This correction is always positive.

For observations of celestial bodies on the horizon, the total correction for zero height of eye is:

Sun: Lower limb: (–)18', upper limb: (–)50'.
Moon: Lower limb: (+)39', upper limb: (+)7'.
Planet/star: (–)34'.

Dip should be added algebraically to these values.

Since the "sextant" altitude is zero, the "observed" altitude is equal to the total correction.

2610. Sight Reduction

Sight reduction tables should be used, if available. If not, use the compact sight reduction tables found in the *Nautical Almanac*. If trigonometric tables and the necessary formulas are available, they will serve the purpose. Speed in solution is seldom a factor in a lifeboat, but might be important aboard ship, particularly in hostile areas. If tables but no formulas are available, determine the mathematical knowledge possessed by the crew. Someone may be able to provide the missing information. If the formulas are available, but no tables, approximate natural values of the various trigonometric functions can be obtained graphically. Graphical solution of the navigational triangle can be made by the orthographic method explained in the chapter on Navigational Astronomy. A maneuvering board might prove helpful in the graphical solution for either trigonometric functions or altitude and azimuth. Very careful work will be needed for useful results by either method. Unless full navigational equipment is available, better results might be obtained by making separate determinations of latitude and longitude.

2611. Latitude Determination

Several methods are available for determining latitude; none requires accurate time.

Latitude can be determined using a **meridian altitude** of any body, if its declination is known. If accurate time, knowledge of the longitude, and an almanac are available, the observation can be made at the correct moment, as determined in advance. However, if any of these is lacking, or if an accurate altitude-measuring instrument is unavailable, a better procedure is to make a number of altitude observations before and after meridian transit. Then plot altitude versus time on graph paper, and the highest (or lowest, for lower transit) altitude is scaled from a curve faired through the plotted points. At small boat speeds, this procedure is not likely to introduce a significant error. The time used for plotting the observations need not be accurate, as elapsed time between observations is all that is needed, and this is not of critical accuracy. Any altitudes that are not consistent with others of the series should be discarded.

Latitude by Polaris is explained in Chapter 20, Sight Reduction. In an emergency, only the first correction is of practical significance. If suitable tables are not available,

Altitude	5°		6°		7°		8°		10°		12°		15°		21°		33°		63°		90°
Refraction		9'		8'		7'		6'		5'		4'		3'		2'		1'		0	

Table 2609. Refraction.

this correction can be estimated. The trailing star of Cassiopeia (∈ Cassiopeiae) and Polaris have almost exactly the same SHA. The trailing star of the Big Dipper (Alkaid) is nearly opposite Polaris and ∈ Cassiopeiae. These three stars, ∈ Cassiopeiae, Polaris, and Alkaid, form a line through the pole (approximately). When this line is horizontal, there is no correction. When it is vertical, the maximum correction of 56' applies. It should be added to the observed altitude if Alkaid is at the top, and subtracted if ∈ Cassiopeiae is at the top. For any other position, estimate the angle this line makes with the vertical, and multiply the maximum correction (56') by the factor from Table 2604, adding if Alkaid is higher than ∈ Cassiopeiae, and subtracting if it is lower. For more accurate results, the factor from Table 2604 can be considered accurate to one additional decimal for the mid-value between those tabulated (except that 1.00 is correct for 0° and 0.00 for 90°). Other values can be found by interpolation.

The **length of the day** varies with latitude. Hence, latitude can be determined if the elapsed time between sunrise and sunset can be accurately observed. Correct the observed length of day by adding 1 minute for each 15' of longitude traveled toward the east and subtracting 1 minute for each 15' of longitude traveled toward the west. The latitude determined by length of day is the value for the time of meridian transit. Since meridian transit occurs approximately midway between sunrise and sunset, half the interval may be observed and doubled. If a sunrise and sunset table is not available, the length of daylight can be determined graphically using a diagram on the plane of the celestial meridian, as explained in Chapter 15. A maneuvering board is useful for this purpose. This method cannot be used near the time of the equinoxes and is of little value near the equator. The moon can be used if moonrise and moonset tables are available. However, with the moon, the half-interval method is of insufficient accuracy, and allowance should be made for the longitude correction.

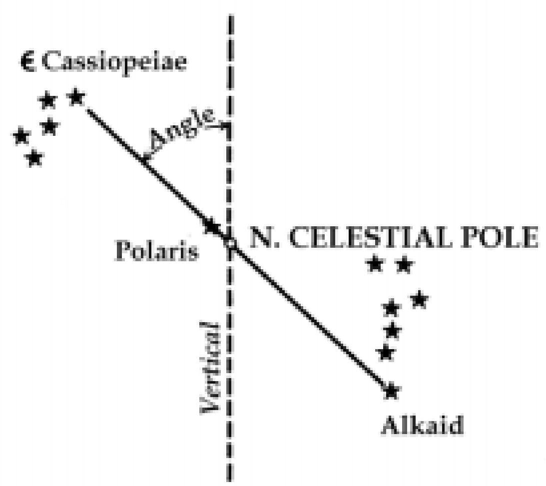

Figure 2611. Relative positions of ∈ Cassiopeiae, Polaris, and Alkaid with respect to the north celestial pole.

The declination of a **body in zenith** is equal to the latitude of the observer. If no means are available to measure altitude, the position of the zenith can be determined by holding a weighted string overhead.

2612. Longitude Determination

Unlike latitude, determining longitude requires accurate Greenwich time. All such methods consist of noting the Greenwich time at which a phenomenon occurs locally. In addition, a table indicating the time of occurrence of the same phenomenon at Greenwich, or equivalent information, is needed. Three methods may be used to determine longitude.

When a body is on the local celestial meridian, its GHA is the same as the longitude of the observer if in west longitude, or 360 - λ in east longitude. Thus, if the GMT of local **time of transit** is determined and a table of Greenwich hour angles (or time of transit of the Greenwich meridian) is available, longitude can be computed. If only the equation of time is available, the method can be used with the sun. This is the reverse of the problem of finding the time of transit of a body. The time of transit is not always apparent. If a curve is made of altitude versus time, as suggested previously, the time corresponding to the highest altitude is used in the determination of longitude. Under some conditions, it may be preferable to observe an altitude before meridian transit, and then again after meridian transit, when the body has returned to the same altitude as at the first observation. Meridian transit occurs midway between these two times. A body in the zenith is on the celestial meridian. If accurate azimuth measurement is available, note the time when the azimuth is 000° or 180°.

The difference between the observed GMT of **sunrise or sunset** and the LMT tabulated in the almanac is the longitude in time units, which can then be converted to angular measure. If the *Nautical Almanac* is used, this information is tabulated for each third day only. Greater accuracy can be obtained if interpolation is used for determining intermediate values. Moonrise or moonset can be used if the tabulated LMT is corrected for longitude. Planets and stars can be used if the time of rising or setting can be determined. This can be computed, or approximated using a diagram on the plane of the celestial meridian (See Chapter 15, Navigational Astronomy).

Either of these methods can be used in reverse to set a watch that has run down or to check the accuracy of a watch if the longitude is known. In the case of a meridian transit, the time need not be determined at the instant of transit. The watch is started, and the altitude is then measured several times before and after transit, or at equal altitudes before and after. The times of these observations are noted, and from them the time of meridian transit is determined. The difference between this time and the correct time of transit can then be used as a correction to reset the watch.