CHAPTER 33

POLAR NAVIGATION

POLAR REGIONS

3300. Introduction

The complex challenge of clearly defining the limits of Earth’s polar regions is problematic, yielding diverse conclusions determined by the different desires of interested parties. Astronomically, the parallels of latitude at which the sun becomes circumpolar (the Arctic and Antarctic Circles at about latitude 67.5°) are considered the lower limits. As of December 27, 2016, the lower limit runs 66°33’46.5” north of the Equator. Its latitude depends on the Earth's axial tilt, which fluctuates within a margin of 2° over a 40,000-year period, due to tidal forces resulting from the orbit of the Moon. Consequently, the Arctic Circle is currently drifting northwards at a speed of about 15 m (49 ft) per year.

Meteorologically, however, the limits are irregular lines which, in the Arctic, coincides approximately with the tree line. For general purposes, the navigator may consider polar regions as extending from the geographical poles of the earth to latitude 75° (in the Arctic coinciding approximately with the northern coast of Alaska). These areas are considered “high latitude” by the U.S. Navy. Transitional **subpolar regions** extending for an additional 10° (in the Northern Hemisphere extending to the southern tip of Greenland).

This chapter deals primarily with marine navigation in high latitudes.

3301. A Changing Landscape in the Arctic

Scientific research and projections of the changes taking place in the Arctic vary, but there is a general consensus that Arctic sea ice is diminishing. As recently as September 2011, scientists at the U.S. National Snow and Ice Data Center reported that the annual Arctic minimum sea ice extent for 2011 was the second lowest in the satellite record, and 938,000 square miles below the 1979 to 2000 average annual minimum. Much of the Arctic Ocean remains ice-covered for a majority of the year, but some scientists have projected that the Arctic may be ice-diminished for periods of time in the summer by as soon as 2040.

The environmental changes taking place in the Arctic are making maritime transit more feasible and are increasing the likelihood of further expansion of human activity, including tourism, oil and gas extraction, commercial shipping, and fishing in the region. For example, in 2011, northern trans-shipping routes opened during the summer months, which permitted more than 40 vessels to transit between June and October. The Northern Sea Route opened in mid-August, and appeared to remain open through September, while the Northwest Passage opened for periods in the summer for the fifth year in a row. See Figure 3301 for locations of these shipping routes.

Despite these changes, several enduring characteristics still provide challenges to surface navigation in the Arctic, including large amounts of winter ice and increased movement of ice from spring to fall. Increased movement of sea ice makes hazard reporting less predictable, a situation that is likely to increase the risk for ships to become trapped or damaged by the ice. This chapter provides a description of these challenges to polar navigation.

3302. Polar Geography

The north polar region, the Arctic, consists of an elongated central water area slightly less than that of the United States, almost completely surrounded by land (Figure 3302a). Some of this land is high and rugged with permanent ice caps, but part of it is low and marshy when thawed. Underlying permafrost prevents adequate drainage, resulting in large numbers of lakes and ponds and extensive areas of muskeg, which is a soft spongy ground having a characteristic growth of certain types of moss and tufts of grass or sedge. There are also large areas of tundra, low treeless plains with vegetation consisting of mosses, lichens, shrubs, willows, etc., and usually having an underlying layer of permafrost. The northernmost point of land is Kap Morris Jessup, Greenland, about 380 nautical miles from the pole.

The central part of the Arctic Ocean, as the body of water is called, is a basin with about 12,000 feet average depth. However, the bottom is not consistent, having a number of seamounts and deeps. The greatest depth is probably a little more than 16,000 feet. At the North Pole the depth is 14,150 feet. Surrounding the polar basin is an extensive continental shelf, broken only in the area between Greenland and Svalbard (Spitsbergen). The many islands of the Canadian archipelago lie on this shelf. The Greenland Sea, east of Greenland, Baffin Bay, west of Greenland, and the Bering Sea, north of the Aleutians, each has its independent basin. In a sense, the Arctic Ocean is an arm of the Atlantic.

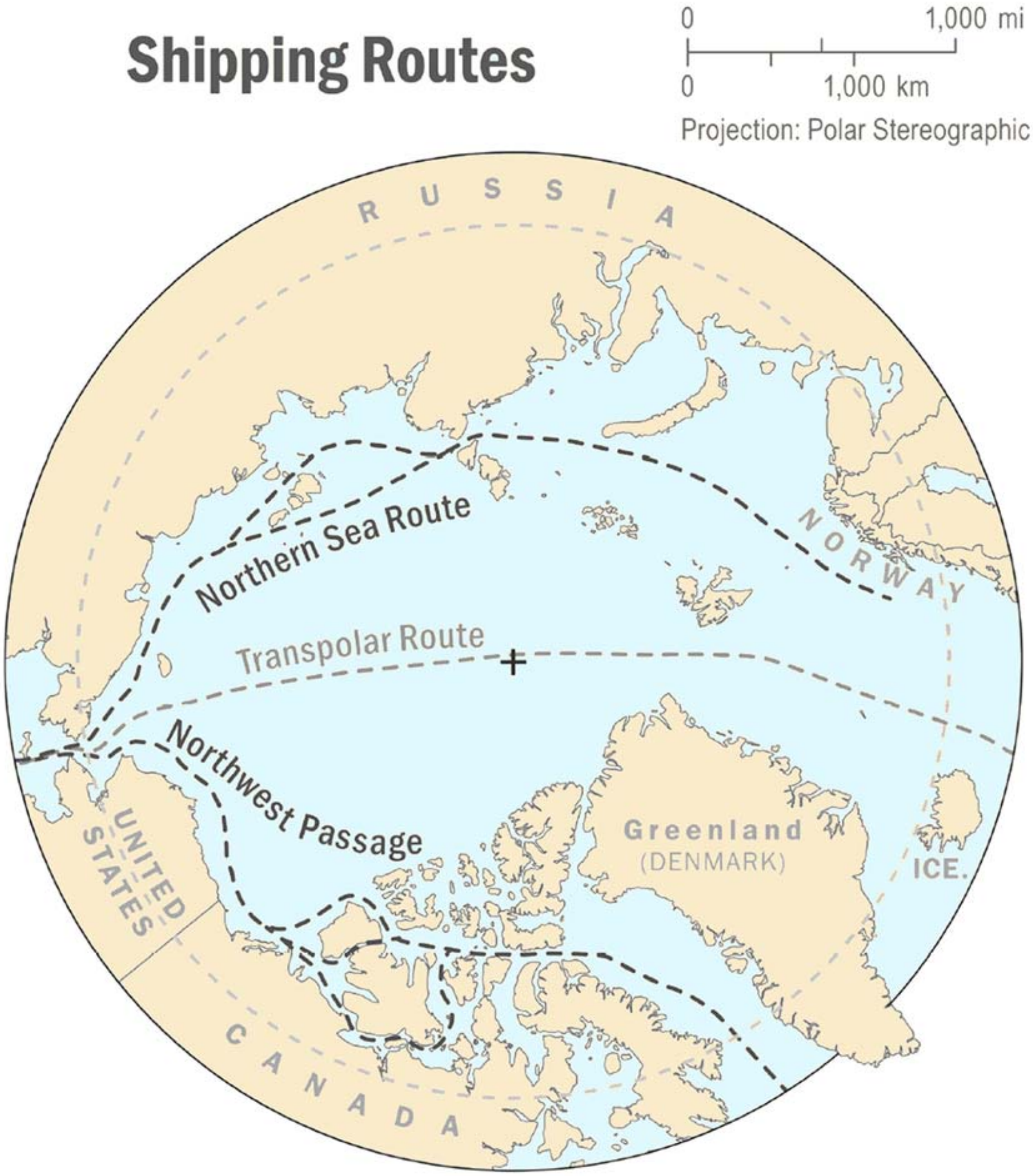

Figure 3301. Polar shipping routes.

The south polar region of the Antarctic is in marked contrast to the Arctic in physiographical features. Here a high, mountainous land mass about twice the area of the United States is surrounded by water (Figure 3302b). An extensive polar plateau covered with snow and ice is about 10,000 feet high. There are several mountain ranges with peaks rising to heights of more than 13,000 feet. The average height of Antarctica is about 6,000 feet, which is higher than any other continent. The height at the South Pole is about 9,500 feet. The barrier presented by land and tremendous ice shelves 500 to 1,000 feet thick prevent ships from reaching very high latitudes. Much of the coast of Antarctica is high and rugged, with few good harbors or anchorages.

3303. Shipping in Polar Waters

While there has historically been regular shipping, especially along the Russian coast in the summer seasons, the amount of shipping and traffic in the Arctic has increased substantially over the last decade. The increase is due to many factors, including interest in the arctic environment, tourism, oil and gas exploration, and exploitation. This has been allowed by the overall reduction in sea ice for greater parts of the year, and the potential for reduced shipping costs using the arctic sea routes.

There are two major surface routes through the Arctic, the Northwest Passage (NWP) along the Canadian

Figure 3302a. The Arctic Ocean floor and surrounding land masses.

Archipelago, and the Russian Federation Northern Sea Route (NSR). See Figure 3301.

All NWP passages have common eastern and western approaches. In the east, ships must proceed through the Labrador Sea, Davis Strait and Baffin Bay. In the western approaches ships proceed through the Bering Sea, Bering Strait, the Chukchi Sea and the Beaufort Sea before deciding which route to follow. In general, the operating season is short (from late July to mid-October) depending on the route and year. Of the various passages listed below, routes 1 and 2 are considered deep water ones, while the others have limiting shoals and rocks restricting the draft of vessels to less than 10 meters.

Routes Through the NWP

1. Routing (East to West): Lancaster Sound - Barrow Strait - Viscount Melville Sound - Prince of Wales Strait - Amundsen Gulf.
2. Routing (East to West): Same as 1 but substitute M'Clure Strait for Prince of Wales Strait and Amundsen Gulf. Collectively Lancaster Sound - Barrow Strait - Viscount Melville Sound is known as Parry Channel.
3. Routing (East to West): Lancaster Sound - Barrow Strait - Peel Sound - Franklin Strait - Larsen Sound - Victoria Strait - Queen Maud Gulf - Dease Strait - Coronation Gulf - Dolphin and Union Strait - Amundsen Gulf.

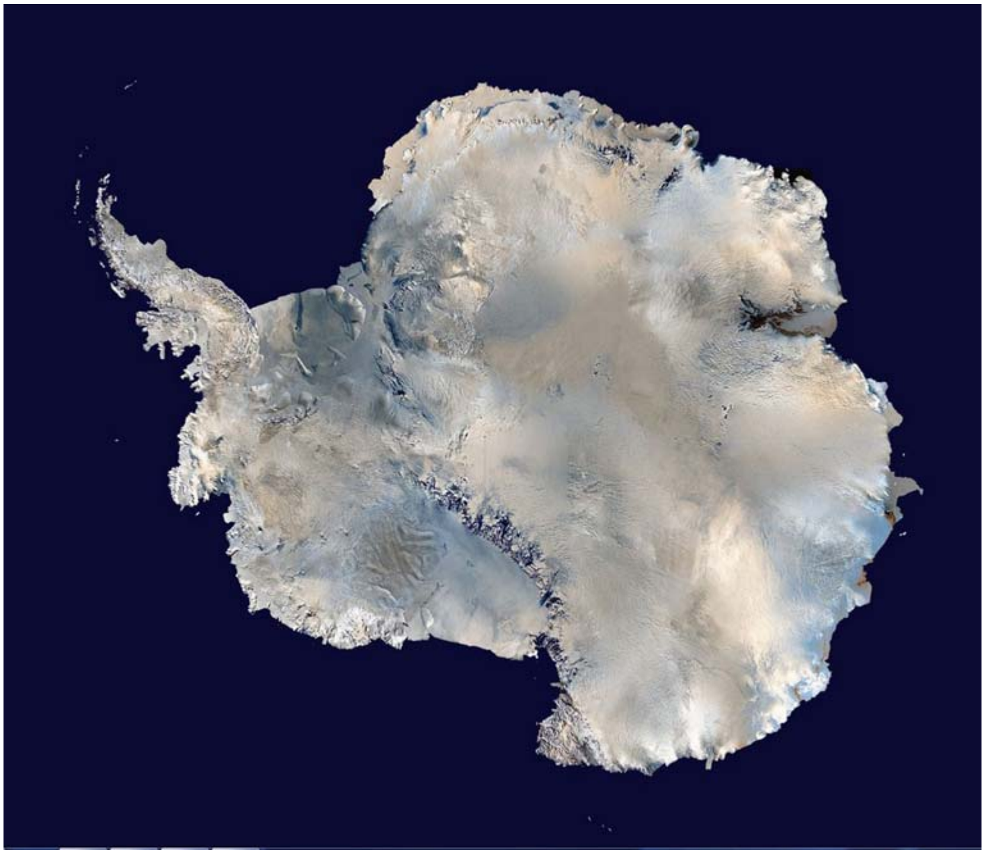

Figure 3302b. A satellite composite image of Antarctica.

4. Routing (East to West): A variation of 3. Rather than following Victoria Strait on the west side of King William Island, the route passes to the east of the island following James Ross Strait - Rae Strait - Simpson Strait.
5. Routing (East to West): Similar to 3. Rather than following Peel Sound on the west side of Somerset Island, the route passes to the east of the island through Prince Regent Inlet and Bellot Strait.
6. Routing (East to West): Hudson Strait - Foxe Channel - Foxe Basin - Fury and Hecla Strait - Gulf of Boothia - Bellot Strait - remainder via routes 3, 4 or 5.

The Russian Federation NSR is a shipping route officially defined by Russian legislation as lying east of Novaya Zemlya and specifically running along the Russian Arctic coast from the Kara Sea, along Siberia, to the Bering Strait. The entire route lies in Arctic waters and within Russia's Exclusive Economic Zone (EEZ). Parts are free of ice for only two months per year.

3304. Polar Code

To support increases in shipping traffic the International Maritime Organization (IMO) adopted the International Code for Ships Operating in Polar Waters (Polar Code) and related amendments to make it mandatory under both the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). The Polar Code is intended to cover the full range of shipping-related matters relevant to navigation in waters surrounding the two poles including: ship design, construction and equipment; operational and training concerns; search and rescue; and, equally important, the protection of the unique environment and eco-systems of the polar regions. The Polar Code is available online via the link provided in Figure 3304.

Figure 3304. The Polar Code http://www.imo.org/en/MediaCentre/HotTopics/polar/Documents/POLAR%20CODE%20TEXT%20AS%20ADOPTED.pdf

3305. High-Latitude Effects

Special techniques have been developed to adapt navigation to the unique conditions of polar regions. These conditions are largely the result of high latitude, the environment and meteorological factors.

Much of the thinking of the marine navigator is in terms of the "rectangular" world of the Mercator projection, on which the meridians are equally spaced, vertical lines perpendicular to the horizontal parallels of latitude. Directions are measured relative to the meridians, and are maintained by means of a magnetic or gyrocompass. A straight line on the chart is a rhumb line, the line used for ordinary purposes of navigation. Celestial bodies rise above the eastern horizon, climb to a maximum altitude often high in the sky as they cross the celestial meridian, and set below the western horizon. By this motion the sun divides the day naturally into two roughly equal periods of daylight and darkness, separated by relatively short transitional periods of twilight. The hour of the day is associated with this daily motion of the sun.

In polar regions conditions are different. Meridians all converge at the poles, which are centers of a series of concentric circles constituting the parallels of latitude. The rapid convergence of the meridians renders the usual convention of direction inadequate for some purposes. A rhumb line is a curve which differs noticeably from a great circle, even for short distances. Even visual bearings cannot adequately be represented as rhumb lines. At the pole all directions are south or north, depending upon the pole. Direction in the usual sense is replaced by longitude. The mariner must also remember that the geographic pole and the magnetic pole are not coincidental.

At the pole the **zenith** and **celestial pole** coincide. Hence, the celestial horizon and celestial equator also coincide, and declination and computed altitude are the same. Therefore, celestial bodies change computed altitude only by changing declination. Stars circle the sky without noticeable change in altitude. Planets rise and set once each sidereal period (12 years for Jupiter, 30 years for Saturn). At the North Pole the sun rises about March 21, slowly spirals to a maximum altitude of about 23°27' near June 21, slowly spirals downward to the horizon about September 23, and then disappears for another six months. At the South Pole, a similar cycle takes place, but during the opposite time of year. It requires about 32 hours for the sun to cross the horizon, during which time it circles the sky 1 and 1/3 times. The twilight periods following sunset and preceding sunrise last for several weeks. The moon rises and sets about once each month. Only celestial bodies of north declination are visible at the North Pole; only bodies of south declination are visible at the South Pole.

The long polar night is not wholly dark. The full moon at this time rises relatively high in the sky. Light from the **aurora borealis** in the Arctic and the **aurora australis** in the Antarctic is often quite bright, occasionally exceeding that of the full moon (see Figure 3305a). Even the planets and stars contribute an appreciable amount of light in this area where a snow cover provides an excellent reflecting surface.

All time zones, like all meridians, meet at the poles. Local time does not have its usual significance, since the hour of the day bears no relation to periods of light and darkness or to altitude of celestial bodies.

Figure 3305a. Aurora borealis above Lyngenfjorden, Norway in March 2012. Image by Simo Räsänen, Wikimedia Commons.

3306. Meteorological Effects

Polar regions are cold, but the temperature at sea is not as extreme as inland. The average winter temperature over the Arctic Ocean is - 30°F to - 40°F, with an extreme low value near - 60°F. Colder temperatures have been recorded in Yellowstone National Park. During the summer the temperature remains above freezing over the ocean. Inland, extreme values are sometimes reached. At least one point on the Arctic Circle has experienced a temperature of 100°F. Few points on the Antarctic Continent have recorded temperatures above freezing, and the interior is probably the coldest part of the world.

Fog and clouds are common in polar regions, yet there is less precipitation than in some desert regions, since the cold air has small capacity for holding moisture. Very cold air over open water sometimes produces steaming of the surface, occasionally to a height of several hundred feet. This is called frost smoke or **sea smoke**. When there is no fog or frost smoke, the visibility is often excellent. Sounds can sometimes be heard at great distances.

Sharp discontinuities or inversions in the temperature lapse rate sometimes produce a variety of mirages and extreme values of refraction. The sun has been known to rise several days before it was expected in the spring. False horizons are not uncommon.

Strong winds are common in the subarctic and in both the Antarctic and subantarctic. The belt of water surrounding Antarctica has been characterized as the stormiest in the world, being an area of high winds and high seas. Strong winds are not encountered over the Arctic Ocean.

In the polar and subpolar regions the principal hazard to ships is ice, of which was both formed at sea or of land ice that flowed into the sea in the form of glaciers. Many low land areas are ice-free in summer. Ice is considered in more detail in Chapter 32.

When snow obliterates surface features, and the sky is covered with a uniform layer of cirrostratus or altostratus clouds, so that there are no shadows, the horizon disappears and earth and sky blend together, forming an unbroken expanse of white, without features. In these conditions landmarks cannot be distinguished, and with complete lack of contrast, distance is virtually impossible to estimate. This phenomenon is called arctic (or antarctic) **white out**. It is particularly prevalent in northern Alaska during late winter and early spring.

3307. Arctic Currents

The cold surface water of the Arctic Ocean flows outward between Greenland and Svalbard and is replaced by warmer subsurface water from the Atlantic. The surface currents depend largely upon the winds, and are generally quite weak in the Arctic Ocean. However, there are a number of well-established currents flowing with considerable consistency throughout the year. The general circulation in the Arctic is clockwise on the American side and around islands, and counterclockwise on the Asian side. Tidal ranges in this area are generally small. In the restricted waters of the upper Canadian-Greenland area both tides and currents vary considerably from place to place. In the Baffin Bay-Davis Strait, the currents are strong and the tides are high, with a great difference between springs and neaps. In the Antarctic, currents are strong and the general circulation offshore is eastward or *clockwise* around the continent. Close to the shore, a weaker westerly, or *counterclockwise,* current may be encountered, but there are many local variations.

3308. Magnetic Poles

Since both magnetic poles are situated within the polar regions, the horizontal intensity of the earth's magnetic field is so low that the magnetic compass is of reduced value, and even useless in some areas.

The magnetic storms centered in the auroral zones disrupt radio frequency navigation and communications and alter magnetic compass sensibility. The frozen ground in polar regions is a poor conductor of electricity, another factor adversely affecting radio wave propagation.

3309. Summary of Conditions in Polar Regions

The more prominent characteristic features associated with large portions of both polar regions may be summarized as follows:

1. High latitude.
2. Rapid convergence of meridians.
3. Nearly horizontal diurnal motion of celestial bodies.
4. Long periods of daylight, twilight, and semi-darkness.
5. Low mean temperatures.
6. Short, cool summers and long, cold winters.
7. High wind-chill factor.
8. Low evaporation rate.
9. Scant precipitation.
10. Dry air (low absolute humidity).
11. Excellent sound-transmitting conditions.
12. Periods of excellent visibility.
13. Extensive fog and clouds.
14. Large number and variety of mirages.
15. Extreme refraction and false horizons.
16. Winter freezing of rivers, lakes, and part of the sea.
17. Areas of permanent land and sea ice.
18. Areas of permanently frozen ground.
19. Large areas of tundra (Arctic).
20. Large areas of poor drainage, with many lakes and ponds (Arctic).
21. Large areas of muskeg (a grassy marsh when thawed) (Arctic).
22. Extensive auroral activity.
23. Large areas of low horizontal intensity of earth's magnetic field.
24. Intense magnetic storms.
25. Uncertain radio wave propagation.
26. Strong winds (Antarctic).
27. Frequent blizzards (Antarctic).
28. Large quantities of blowing snow.

CHARTS

3310. Projections

When navigating in polar regions, as elsewhere, charts are an indispensable component. Chart projections used for polar navigation are covered in Chapter 4, Sections 420 and 421. With the advent of modern electronic charting and voyage management systems, much of the traditional methods of positioning, such as manual computation and hardcopy plotting, are now reduced or eliminated through automation. Prudent mariners using electronic charting methods will familiarize themselves with their system's polar navigation modes prior to use, and will fully understand alternative program utilities and limitations per manufacturer specifications in order to guarantee system functionality in high latitudes.

For ordinary navigation the Mercator projection has long been the overwhelming favorite of marine navigators, primarily because a rhumb line appears as a straight line on this projection. Even in high latitudes the mariner has exhibited an understandable partiality for Mercator charts, which have been used virtually everywhere ships have gone.

However, as the latitude increases, the utility of the Mercator projection decreases, primarily because the value of the rhumb line becomes progressively less accurate. At latitudes greater than 60° the decrease in utility begins to be noticeable, and above latitude 70° it becomes problematic. In the clear polar atmosphere, visual bearings can be observed at great distances, sometimes 50 miles or more, but the use of a rhumb line to represent a bearing line introduces an error at any latitude, and at high latitudes errors become exaggerated.

Another objection to Mercator charts at high latitudes is the increasing rate of change of scale over a single chart. This results in distortion in the shape of land masses and errors in measuring distances.

At some latitudes the disadvantages of the Mercator projection outweigh its advantages. The latitude at which this occurs depends upon the physical features of the area, the configuration and orientation of land and water areas, the nature of the operation, and the experience and personal preference of the mariner. Because of differences of opinion on this matter, a transitional zone exists in which several projections may be encountered. The wise high-latitude navigator is prepared to use any of them, since coverage of the operating area may not be adequate on their favorite projection.

There are currently (2017) no standard projection recommended for polar marine operations, but this is expected to change in the near future with the increase in commercial activity in the Arctic. See Figure 3310 for link to more detailed information regarding suitable projections for navigation in the Arctic, including the use of ECDIS.

Figure 3310. Choosing Suitable Projections for Navigation in the Arctic by the National Technical University of Athens. http://www.iho.int/mtg_docs/rhc/ArHC/ArHC3/ARHC3-3.2.7_Suitable_projections_for_the_Arctic.pdf

Projections commonly used for polar charts are the modified Lambert Conformal, the Gnomonic, the Stereographic and the Azimuthal Equidistant. These projections are similar near the pole. They are essentially conformal, and a great circle on each is nearly a straight line. As the distance from the pole increases, however, the distinctive features of each projection become apparent:

a. The modified Lambert conformal projection is conformal over its entire extent. The amount of scale distortion is comparatively small if it is carried only to about 25° or 30° from the pole. Beyond that, the distortion increases rapidly. A great circle is very nearly a straight line anywhere on the chart. Distances and directions can be measured directly on the chart in the same manner as on a Lambert conformal chart. However, because this projection is not strictly conformal, and on it great circles are not exactly represented by straight lines, it is not suited for highly accurate positioning.
b. The Polar Gnomonic projection is the one polar projection on which great circles are exactly straight lines. However, a complete hemisphere cannot be represented upon a plane because the radius of 90° from the center would become infinity.
c. The Polar Stereographic projection is conformal over its entire extent and a straight line closely approximates a great circle. The scale distortion is not excessive for a considerable distance from the pole, but it is greater than that of the modified Lambert conformal projection.
d. The Polar Azimuthal Equidistant projection is useful for showing a large area such as a hemisphere because there is no expansion along the meridians. However, the projection is neither conformal nor equivalent and distances cannot be measured accurately in any but a north-south direction. Great circles other than the meridians differ somewhat from straight lines. The equator is a circle centered at the pole.
e. The two projections most commonly used for polar

charts in traditional navigation are the modified Lambert Conformal and the Polar Stereographic. When a directional gyro is used as a directional reference, the track of the craft approximates a great circle. A desirable chart is one on which a great circle is represented as a straight line with a constant scale and with angles correctly represented. These requirements are not met entirely by any single projection, but they are approximated by the modified Lambert Conformal, the Polar Stereographic and the Azimuthal Polar Equidistant. The scale is more nearly constant on the Polar Equidistant, but the projection is not strictly conformal. The Polar Stereographic is conformal, and its maximum scale variation can be reduced by using a plane which intersects the earth at some parallel intermediate between the pole and the lowest parallel. The portion within this standard parallel is compressed and that portion outside is expanded.

3311. Adequacy

NOAA-provided charts and Coast Pilots are either unavailable or outdated for areas in the Arctic. Until recently, most of this region was relatively inaccessible by ship due to the presence of thick, impenetrable sea ice. Further, most Arctic waters that are charted were surveyed with imprecise technology, dating back to the 1800s. Most of the shoreline along Alaska's northern and western coasts has not been surveyed since 1960. As a result, confidence in the region's nautical charts is low. It is estimated by the Canadian Hydrographic Service (CHS) that less than 25% of the Arctic waters are surveyed to acceptable, modern standards. Much of the data is a collection of random vessel track soundings or over-ice spot soundings.

Modern U.S. navigational charts are a compilation of the best data available. Nevertheless, many of the soundings on the charts are from as early as the 1800s. Because transportation activities have increased in Arctic seaways, NOAA has been working to update outdated Arctic nautical charts to meet modern needs. In 2011, NOAA issued an *Arctic Nautical Charting Plan* after consultations with maritime interests and the public, as well as with other federal, state, and local governments. NOAA updated the plan in 2013, outlining the creation of 14 new charts to complement existing chart coverage. Since the update, NOAA released a new nautical chart for the Arctic, helping mariners navigate the Bering Strait. Chart 16190 (Bering Strait North) incorporates precise depth measurements acquired recently by NOAA Ship Fairweather hydrographic surveys.

On October 6, 2010, NOAA led a U.S. delegation that formally established a new Arctic Regional Hydrographic Commission (ARHC) with four other nations known (together with the U.S.) as “Arctic coastal states.” The commission, which also includes Canada, Denmark, Norway, and the Russian Federation, promotes cooperation in hydrographic surveying and nautical charting. The Commission provides a forum for better collaboration to ensure safety of life at sea, protect the increasingly fragile Arctic ecosystem, and support the maritime economy.

Charts of most polar areas are generally inferior to those of other regions in at least three respects:

1. *Lack of detail*. Polar regions have not been surveyed with the thoroughness needed to provide charts with traditional detail. Relatively few soundings are available and many of the coastal features are shown by their general outlines only. Large areas are perennially covered by ice, which presents a changing appearance as the position and character of the ice changes. Heavy ice cover and snow prevent accurate determination of surface features of the earth beneath. Added to this is the similarity between adjacent land features where the hundreds of points and fiords in one rugged area or the extensive areas of treeless, flat coastal land in another look strikingly alike. The thousands of shallow lakes and ponds along a flat coastal plain also lack distinctive features.
2. *Inaccuracy*. Polar charts are based upon incomplete surveys and reports of those who have been in the areas. These reports are less reliable than in other areas because icebergs are sometimes mistaken for islands, ice-covered islands are mistaken for grounded icebergs, shorelines are not easy to detect when snow covers both land and attached sea ice, inlets and sounds may be completely obscured by ice and snow, and meteorological conditions may introduce inaccuracy in determination of position. Consequently, many features are inaccurately shown in location, shape, and size, and there are numerous omissions. Isogonic lines, too, are based upon incomplete information, resulting in less than desired accuracy.
3. *Coverage*. Relatively few nautical charts of polar regions are available, and the limits of some of these are not convenient for some operations. As in other areas, charts have been made as the need has arisen. Hence, large-scale charts of some areas are completely lacking. Aeronautical charts are sometimes quite helpful, as they often show more detail of land areas than do the nautical charts. However, aeronautical charts do not show soundings.
4. *Datum*. Since charts may have not be updated using more modern methods (i.e. GPS) such that the chart datum may be a local one or one used by earlier cartographers (i.e. NAD27). Chart datum shifts may exceed as much as 1 km under worst case circumstances.

3312. Polar Grid

Because of the rapid convergence of the meridians in polar regions, the true direction of an oblique line near the pole may vary considerably over a relatively few miles. The meridians are radial lines meeting at the poles, instead of being parallel, as they appear on the familiar Mercator chart.

Near the pole the convenience of parallel meridians is attained by means of a **polar grid**. On the chart a number of lines are printed parallel to a selected reference meridian, usually that of Greenwich. On transverse Mercator charts the fictitious meridians may serve this purpose. Any straight line on the chart makes the same angle with all grid lines. On the transverse Mercator projection it is therefore a **fictitious rhumb line**. On any polar projection it is a close approximation to a great circle. If north along the reference meridian is selected as the reference direction, all parallel grid lines can be considered extending in the same direction. The constant direction relative to the grid lines is called **grid direction**. North along the Greenwich meridian is usually taken as grid north in both the Northern and Southern Hemispheres.

The value of grid directions is indicated in Figure 3312. In this figure A and B are 400 miles apart. The true bearing of B from A is 023°, yet at B this bearing line, if continued, extends in true direction 163°, a change of 140° in 400 miles. The grid direction at any point along the bearing line is 103°.

When north along the Greenwich meridian is used as grid north, interconversion between grid and true directions is quite simple. Let G represent a grid direction, T the corresponding true direction, λ is longitude and W is the Western Hemisphere. Then for the Arctic,

$$G = T + \lambda W$$

That is, in the Western Hemisphere, in the Arctic, grid direction is found by adding the longitude to the true direction. From this it follows that,

$$T = G - \lambda W$$

and in the Eastern Hemisphere,

$$G = T - \lambda E$$
$$T = G + \lambda E$$

In the Southern Hemisphere the signs (+ or -) of the longitude are reversed in all formulas.

If a magnetic compass is used to follow a grid direction, variation and convergency can be combined into a single correction called **grid variation** or **grivation**. It is customary to show lines of equal grivation on polar charts rather than lines of equal variation. **Isogrivs** are lines of equal grivation.

With one modification the grid system of direction can be used in any latitude. Meridians 1° apart make an angle of 1° with each other where they meet ' at the pole. The **convergency** is one, and the 360°of longitude cover all 360° around the pole. At the equator the meridians are parallel and the convergency is zero. Between these two limits the convergency has some value between zero and one. On a sphere it is equal to the sine of the latitude. For practical navigation this relationship can be used on the spheroidal earth. On a simple conic or Lambert conformal chart a constant convergency is used over the entire chart, and is known as the **constant of the cone**. On a simple conic projection it is equal to the sine of the standard parallel. On a Lambert conformal projection it is equal (approximately) to the sine of the latitude midway between the two standard parallels. When convergency is printed on the chart, it is generally adjusted for ellipticity of the earth. If K is the constant of the cone,

$$K = \sin 1/2(L_1 + L_2)$$

where $L_1$and L_2 are the latitudes of the two standard parallels. On such a chart, grid navigation is conducted as explained above, except that in each of the formulas the longitude is multiplied by K:

$$G = T + K\lambda W,$$
$$T = G - K\lambda W$$
$$G = T - K\lambda E$$
$$T = G + K\lambda E$$

Thus, a straight line on such a chart changes its true direction, not by 1° for each degree of longitude, but by K°. As in higher latitudes, convergency and variation can be combined.

In using grid navigation one should keep clearly in mind the fact that the grid lines are parallel *on the chart*. Since distortion varies on charts of different projections, and on charts of conic projections having different standard parallels, t*he grid direction between any two given points is not the same on all charts*. For operations which are to be coordinated by means of grid directions, *it is important that all charts showing the grid be on a single graticule* (Section 403).

3313. Arctic Navigation Background

Navigation using an inertial navigation system (INS) utilizes a Local Level reference frame to represent heading and velocity quantities. The Local Level reference frame is an Earth-fixed frame, centered on the navigation system center, as in Figure 3313. The axes of the Level Frame are as follows:

Singularities arise as the vessel approaches the North pole, as the local North direction and the local East direc-

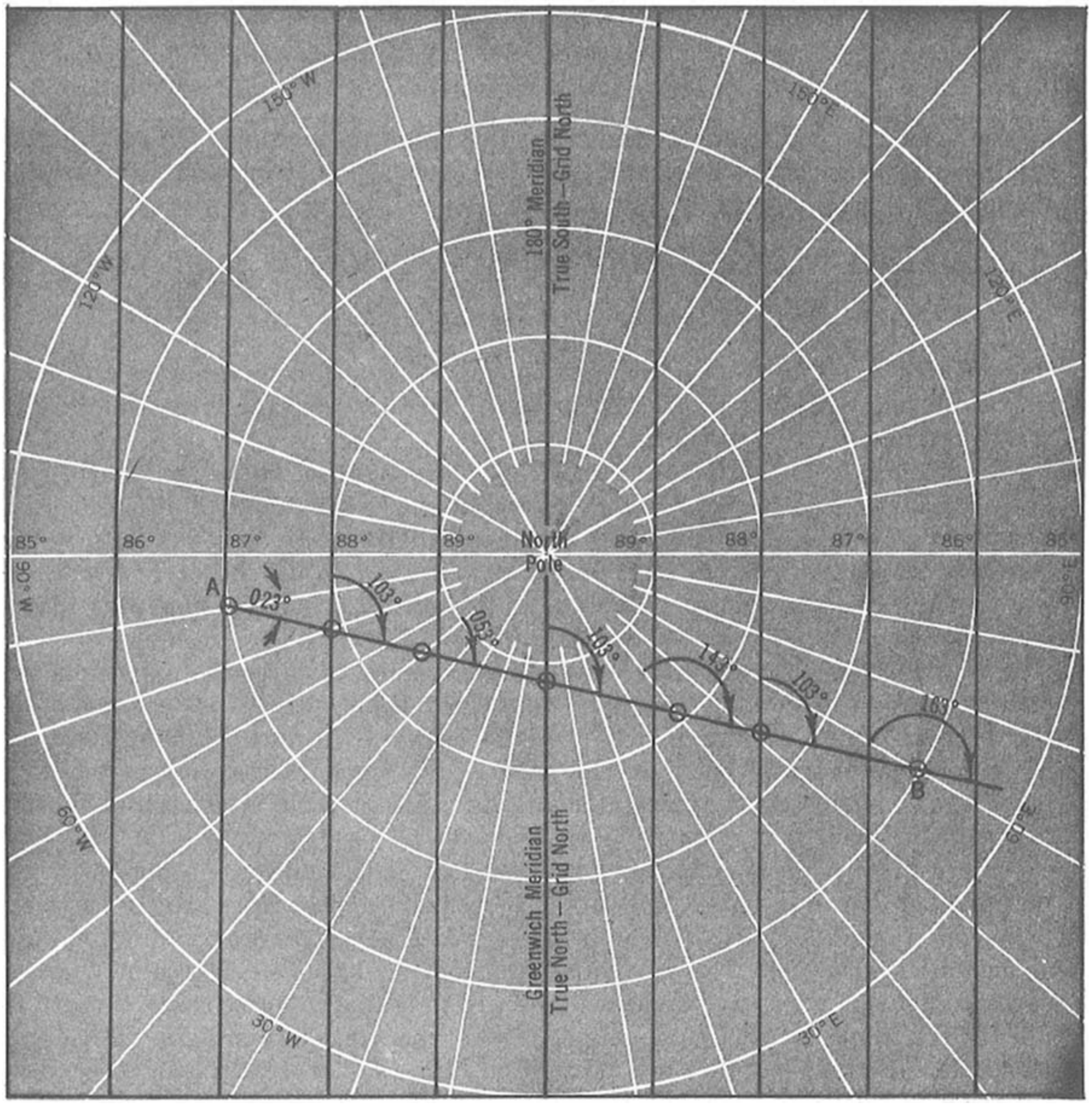

Figure 3312. Polar grid navigation.

tion become undefined. (Navigation equations commonly use the tangent and secant trigonometric functions, which become indeterminate near 90°N (i.e., approach infinity)). To avoid this problem, a different coordinate system is required for operations near the North Pole.

3314. The Transverse Coordinate System

The singularity problem can be avoided by redefining the 'North' location when the vessel nears the poles. Nominally, North is equivalent to the $\ddot{Z}$ axis in the Earth Centered, Earth Fixed (ECEF) coordinate system. If this coordinate system is rotated by -90 degrees about the $\hat{Y}$ axis, a new $\hat{Z}'$axis is created that represents a new North, as shown in Figure 3314.

This new coordinate system is the Transverse Coordinate System. Fortunately, the transverse coordinate process has been automated in many electronic charting and voyage management systems, eliminating the need for the navigator to manually compute coordinate conversions. The following mathematical description of the Transverse Coordinate System is provided for completeness and to aid in understanding the processes that are occurring within the processor.

Ships equipped with INSs are required to switch to Transverse Mode to keep the INS solution from becoming unstable when tangents approach zero and to make heading more useful. Modern INSs should have a

$$\begin{bmatrix} \hat{N} \\ \hat{E} \\ \hat{D} \end{bmatrix} = \begin{matrix} \textit{Local North direction} \\ \textit{Local East direction} \\ \textit{Earth Center direction} \end{matrix}$$

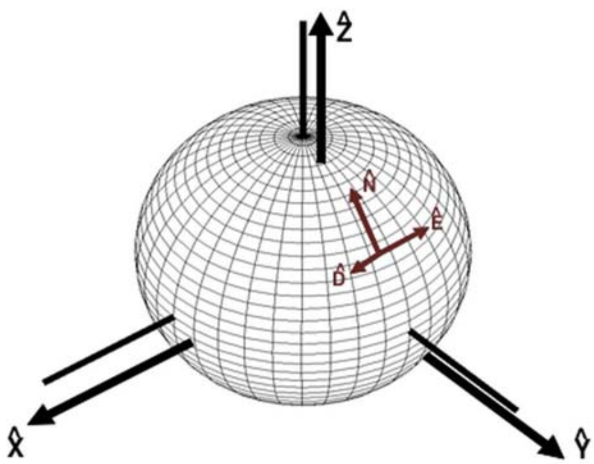

Figure 3313. Local Level and ECEF Frames.

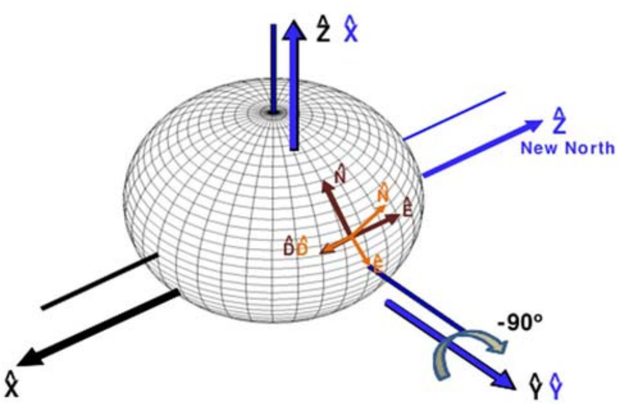

Figure 3314. Transverse and Transverse Local Level Frames.

Transverse Mode capability to generate navigation solutions in the Transverse Coordinate System. Heading, Velocity, and Position all change to Transverse Heading (THD), Transverse North and East Velocity (TNV/TEV), and Transverse Lat/Lon (TLT/TLN) when in a Transverse Mode. Chapter 20 Introduction to Intertial Navigation provides background on how INS works.

The Transverse Coordinate System and is created from the ECEF coordinate system through the following transformation: *Equation 1*

$$\begin{bmatrix} \hat{X}' \\ \hat{Y}' \\ \hat{Z}' \end{bmatrix} = T_E^T \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix}$$

Where the ECEF to Transverse direction cosine matrix is: *Equation 2*

$$T_E^T = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

A new Transverse Local Level frame is now defined as:

$$\begin{bmatrix} \hat{N}' \\ \hat{E}' \\ \hat{D}' \end{bmatrix} = \begin{matrix} \textit{Transverse North direction} \\ \textit{Transverse East direction} \\ \textit{Earth Center direction} \end{matrix}$$

3315. Position

The Transverse Latitude and Transverse Longitude position of the vessel needs to be computed in the new Transverse coordinate system, as North and the Prime Meridian are no longer in the same location. The position in ECEF can be computed from the nominal Latitude (L) and Longitude (λ) from the following: *Equation 3*

$$X = R_\varnothing \cos L \cos \lambda$$
$$Y = R_\varnothing \cos L \sin \lambda$$
$$Z = R_\varnothing \sin L$$

Likewise, the position in the Transverse coordinate system is: *Equation 4*

$$X' = R_\varnothing \cos L' \cos \lambda'$$
$$Y' = R_\varnothing \cos L' \sin \lambda'$$
$$Z' = R_\varnothing \sin L'$$

Where L' and λ' are the Transverse Latitude and Transverse Longitude, respectively, and are the values that need to be computed. $R_\varnothing$ is the Earth radius.

From equation 1, the following relationships hold: *Equation 5*

$$\widehat{X'} = \hat{Z}$$
$$\widehat{Y'} = \hat{Y}$$

$$\hat{Z}' = -\hat{X}$$

Equating the two sides gives: *Equation 6*

$$R_{\varnothing}\cos L'\cos\lambda' = R_{\varnothing}\sin L$$
$$R_{\varnothing}\cos L'\sin\lambda' = R_{\varnothing}\cos L\sin\lambda$$
$$R_{\varnothing}\sin L' = -R_{\varnothing}\cos L\cos\lambda$$

Or, *Equation 7*

$$L' = \sin^{-1}(-\cos L\cos\lambda)$$
$$X' = \tan^{-1}\left(\frac{\sin\lambda}{\tan L}\right)$$

The equation for λ' comes from: *Equation 8*

$$\lambda' = \tan^{-1}\left(\frac{Z'}{X'}\right)$$
$$= \tan^{-1}\left(\frac{R_{\varnothing}\cos L\cos\lambda}{R_{\varnothing}\sin L}\right)$$
$$= \tan^{-1}\left(\frac{\sin\lambda}{\tan L}\right)$$

3316. Vector Transformation

Vectors in Local Level Frame can be represented in the Transverse Local Level frame through a series of transformation matrices: *Equation 9*

$$\begin{bmatrix} a' \\ b' \\ c' \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Where T_T^L and T_N^E are direction cosine matrices representing the transformation from Transverse Frame (*T*) to Transverse Local Level (*L*) and from Local Level (*N*) to ECEF (*E*) frame, respectively. These matrices are defined as: *Equations 10 & 11*

$$T_T^L = \begin{bmatrix} -\sin L'\cos\lambda' & -\sin L'\sin\lambda' & \cos L \\ -\sin\lambda & \cos\lambda' & 0 \\ -\cos L'\cos\lambda' & -\cos L'\sin\lambda' & -\sin L \end{bmatrix}$$

$$T_N^E = \begin{bmatrix} -\sin L\cos\lambda & -\sin\lambda & -\cos L\cos\lambda \\ -\sin L\sin\lambda & \cos\lambda & -\cos L\sin\lambda \\ \cos L & 0 & -\sin L \end{bmatrix}$$

The transformation matrix T_E^T is as defined in Equation 2.

3317. Velocity Transformation

Transforming a velocity from Local Level frame to Transverse Local Level is accomplished by transforming the velocity vector as previously described: *Equation 12*

$$\begin{bmatrix} V'_N \\ V'_E \\ V'_D \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix}$$

3318. Heading Transformation

Heading in the Transverse Local Level frame is referenced to the Transverse North. As such, the nominal Local Level Heading must be transformed. This can be accomplished by creating a unit vector in local level frame as: *Equation 13*

$$\begin{bmatrix} H_N \\ H_E \\ H_D \end{bmatrix} = \begin{matrix} \cos\phi \\ \sin\phi \\ 0 \end{matrix}$$

Where ϕ is the heading.

This is now a vector that can be transformed into Transverse Local Level frame: *Equation 14*

$$\begin{bmatrix} H'_N \\ H'_E \\ H'_D \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} H_N \\ H_E \\ H_D \end{bmatrix}$$

The new Transverse Local Level Heading is: *Equation 15*

$$\phi' = \tan^{-1}\frac{H'_E}{H'_N}$$

3319. Plotting on Polar Charts

Plotting on polar charts, as on other charts, involves the measurement of distance and direction. Fortunately, the transverse coordinate process has been automated in many voyage management and charting systems, eliminating the need for mariner to manual compute and plot positions in transverse coordinates on paper charts. The following information is provided on this manual process for completeness.

On a paper chart with converging meridians, as one on the Lambert conformal projection, distance is measured by

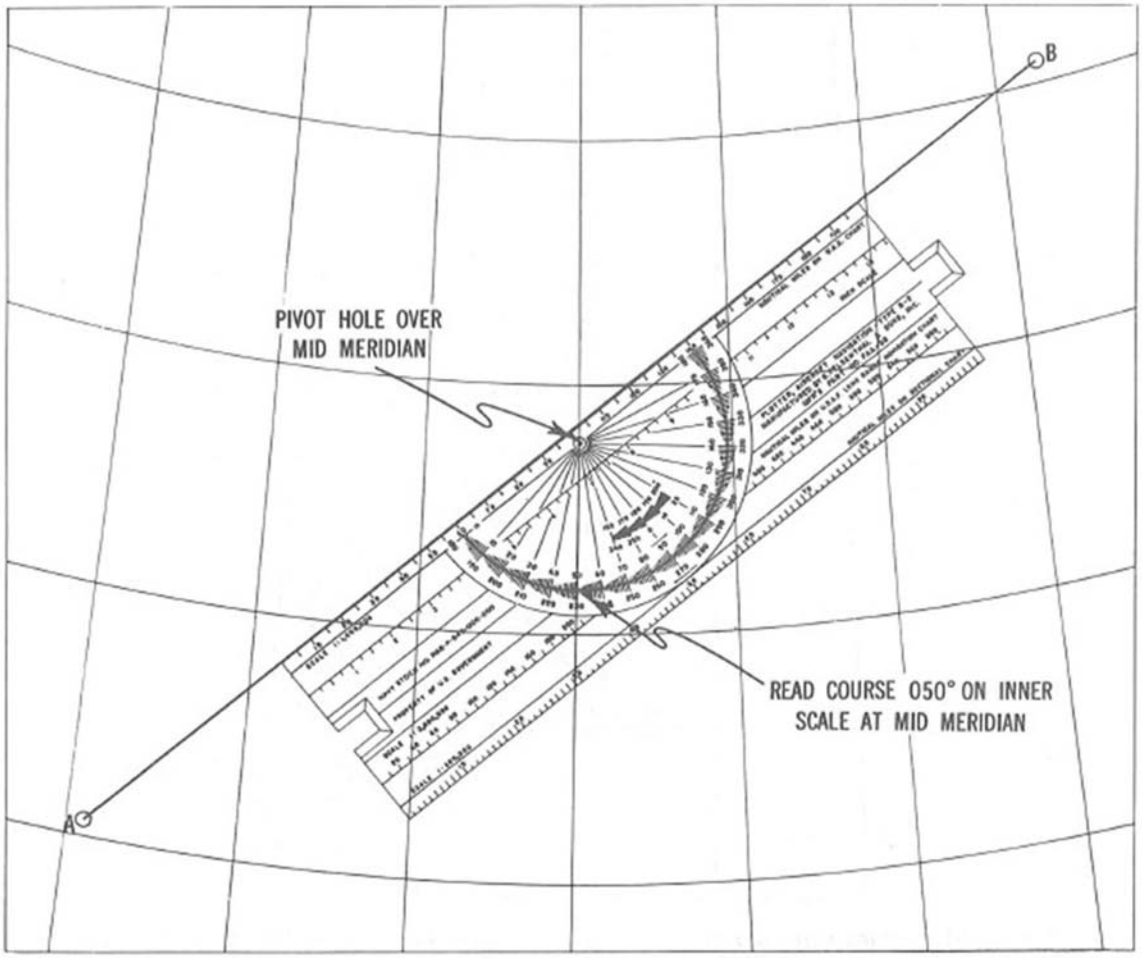

Figure 3319a. Measuring a course on a Lambert conformal chart. Note that the measurement is made at the mid meridian.

means of the latitude scale, as on a Mercator chart, but this scale is so nearly constant that any part of it can be used without introducing a significant error. A mile scale is sometimes shown in or near the margin of such a chart, and can be used anywhere on that chart.

Since the meridians converge, a straight line makes a different angle with each meridian, as shown in Figure 3312. For this reason, compass roses are not customarily shown on such a chart. If they do appear, each one applies only to the meridian on which it is located. The navigator accustomed to using a Mercator chart can easily forget this point, and hence will do well to ignore compass roses. If a drafting machine is used, it should be aligned with the correct meridian each time a measurement is made. Since this precaution can easily be overlooked, especially by navigators accustomed to resetting their drafting machine only when the chart is moved, and since the resulting error may be too small to be apparent but too large to ignore, it is good practice to discard this instrument when the Mercator chart is replaced by one with converging meridians, unless positive steps are taken to prevent error.

The most nearly fool-proof and generally most satisfactory method of measuring directions on a paper chart with converging meridians is to use a protractor, or some kind of plotter combining the features of a protractor and straightedge (Figure 3319a).

If a course is to be measured, the mid meridian of each leg should be used, as shown in Figure 3319a. If a bearing is to be measured, the meridian nearest the point at which the bearing was determined should be used, as shown in Figure 3319b. Thus, in the usual case of determining the bearing of a landmark from a ship, the meridian nearest the ship should be used. In using either of the plotters shown in Figure 3319a or Figure 3319b, note that the center hole is placed over the meridian used, the straightedge part is placed along the line to be drawn or measured, and the angle is read on the protractor at the same meridian which passes under the center hole. It is sometimes more convenient to invert the plotter, so that the protractor part extends on the opposite side of the straightedge.

For plotting grid directions, angles are measured from grid north, using any grid meridian. Any convenient method can be used. If a protractor or plotter is being used for plotting grid directions, it is usually desirable to use the same instrument for plotting true directions. The distance is the same whether grid or true directions are used.

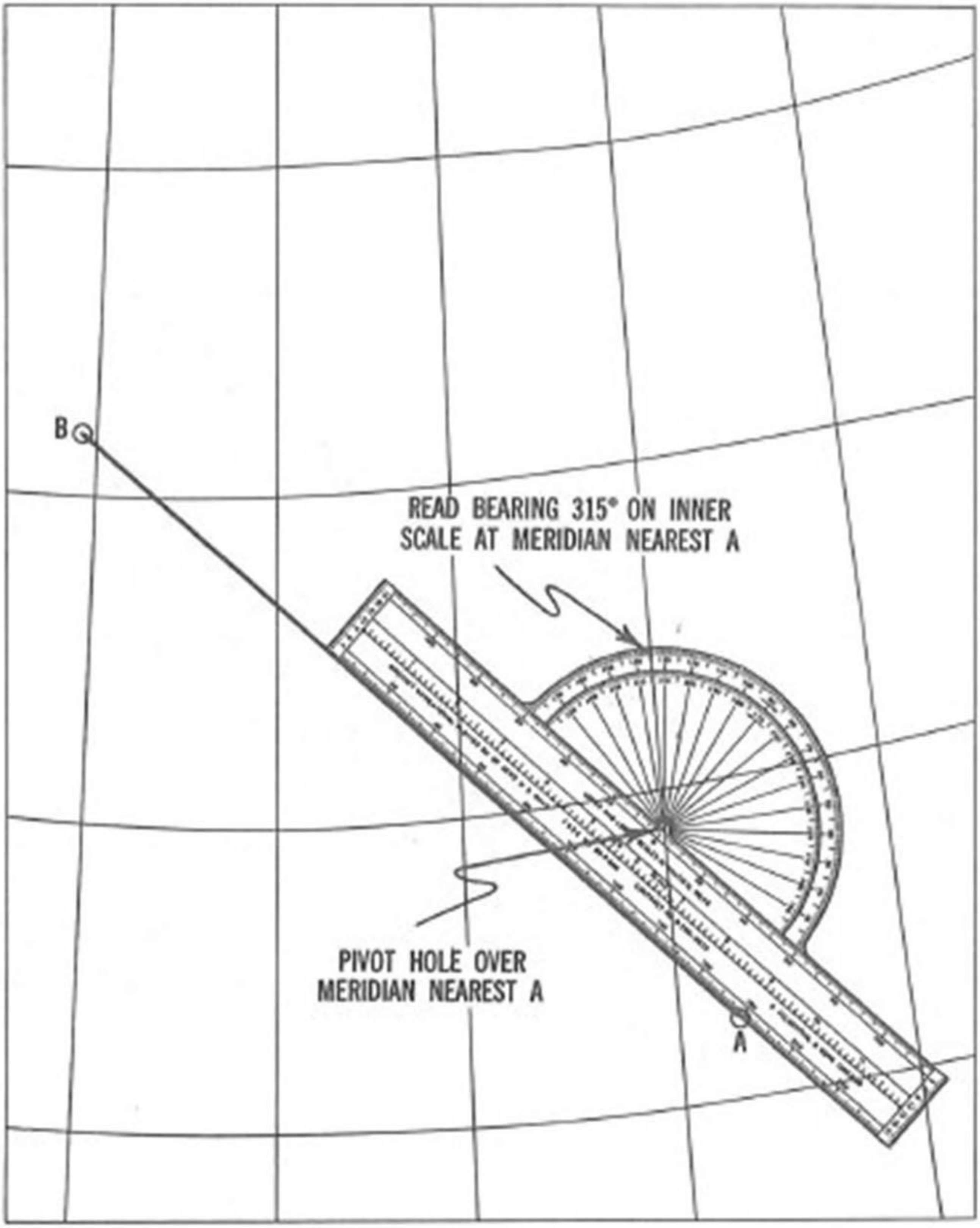

Figure 3319b. Measuring a bearing on a Lambert conformal chart. Note that the measurement is made at the meridian nearest the ship.

DEAD RECKONING

3320. Polar Dead Reckoning

In polar regions, as elsewhere, dead reckoning involves measurement of direction and distance traveled, and the use of this information for determination of position. Direction is normally determined by a compass (magnetic or gyrocompass), but in polar regions both magnetic and gyrocompasses are subject to certain limitations not encountered elsewhere. GNSS Global Navigation Satellite System can also provide an independent direction of movement using satellite signals and vessel motion, but this should not be confused with the actual ship orientation. However, the navigator who thoroughly understands the use of these instruments in high latitudes can get much useful information from them. The polar navigator should not overlook the value of radar tracking or visual tracking for determining direction of motion in the absence of a GNSS. This is discussed in Section 3323.

If GNSS is not available, speed or distance is normally measured by log or engine r evolution counter at normal latitudes. These backup speed measurement methods are not entirely suitable when the ship is operating in ice. The problem of determining speed or distance in ice without GNSS is discussed in Section 3323.

3321. Magnetic Compass

The magnetic compass directive force depends upon the horizontal intensity of the magnetic field of the earth. As the magnetic poles are approached, the opposing force on the compass card becomes progressively weaker until at some point the magnetic compass becomes useless as a direction-measuring device. In a marginal area it is good practice to keep the magnetic compass under almost constant scrutiny, as it will be somewhat erratic in dependability and its errors may change rapidly. Frequent compass checks by celestial observation or any other method available are wise precautions. A log of compass comparisons and observations is useful in predicting future reliability.

The magnetic poles themselves are somewhat elusive, since they participate in the normal diurnal, annual, and secular changes in the earth's field, as well as the more erratic changes caused by magnetic storms. Measurements indicate that the north magnetic pole moves within an elongated area of perhaps 100 miles in a generally north-south direction and somewhat less in an east-west direction. Normally, it is at the southern end of its area of movement at local noon and at the northern extremity twelve hours later, but during a severe magnetic storm this motion is upset and becomes highly erratic. Because of the motions of the poles, they are sometimes regarded as areas rather than points. There is some evidence to support the belief that several secondary poles exist, although such alleged poles may be anomalies (local attractions), possibly of intermittent or temporary existence. Various severe anomalies have been located in polar areas and others may exist.

The continual motion of the poles may account, at least in part, for the large diurnal changes in variation encountered in high latitudes. Changes as large as 10° have been reported.

The decrease in horizontal intensity encountered near the magnetic poles, as well as magnetic storms, affects the magnetic deviation. Any deviating magnetic influence remaining after adjustment, which is seldom perfect, exerts a greater influence as the directive force decreases. It is not uncommon for residual deviation determined in moderate latitudes to increase 10- or 20-fold in marginal areas. Interactions between correctors and compass magnets exert a deviating influence that may increase to a troublesome degree in high latitudes. The heeling magnet, correcting for both permanent and induced magnetism, is accurately located only for one magnetic latitude. Near the magnetic pole its position might be changed, but this may induce sufficient magnetism in the Flinders bar to more than offset the change in deviation due to the change in the position of the heeling magnet. The relatively strong vertical intensity may render the Flinders bar a stronger influence than the horizontal field of the earth. When this occurs, the compass reading remains nearly the same on any heading.

Another effect of the decrease in the directive force of the compass is a greater influence of frictional errors. This combined with an increase in the period of the compass, results in greatly increased sluggishness in its return to the correct reading after being disturbed. For this reason the compass performs better in a smooth sea free from ice than in an ice-infested area where its equilibrium is frequently upset by impact of the vessel against ice.

Magnetic storms affect the magnetism of a ship as well as that of the earth. Changes in deviation of as much as 45° have been reported during severe magnetic storms, although it is possible that such large changes may be a combination of deviation and variation changes.

The area in which the magnetic compass is of reduced value cannot be stated in specific terms. A magnetic compass in an exposed position performs better than one in a steel pilot house. The performance of the compass varies considerably with the type of compass, sensibility and period, thoroughness of adjustment, location on the vessel, and magnetic properties of the vessel. It also varies with local conditions.

Based on the World Magnetic Model (WMM) 2015 coefficients the geomagnetic north pole is at 72.62°W longitude and 80.37°N latitude, and the geomagnetic south pole is at 107.38°E longitude and 80.37°S latitude. The axis

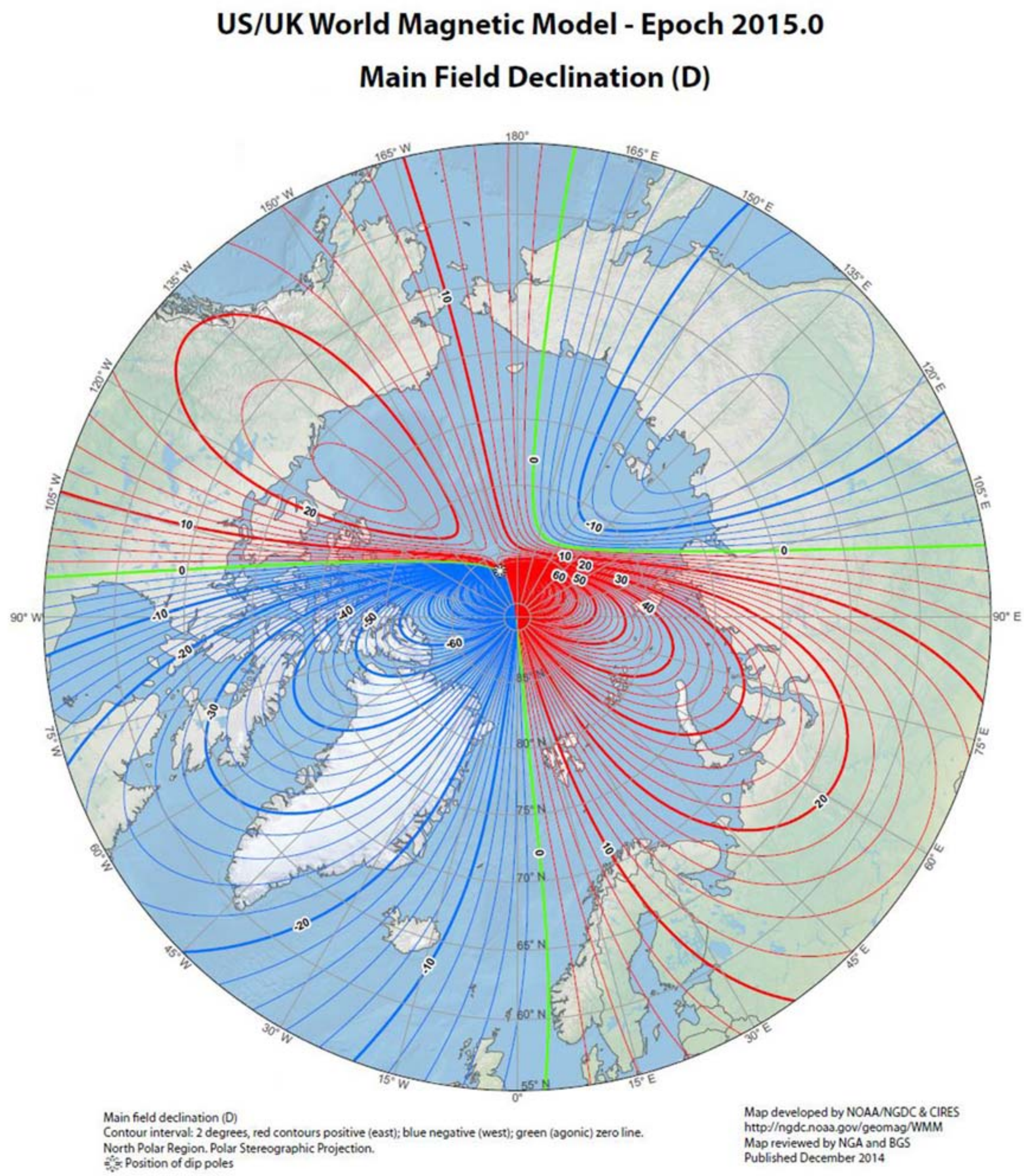

Figure 3321a. Main magnetic field declination for the North pole in 2015.

of the dipole is currently inclined at 9.69° to the Earth's rotation axis. The WMM can also be used to calculate dip pole positions. These model dip poles are computed from all the Gauss coefficients using an iterative method. In 2015 the north dip pole computed from WMM2015 is located at longitude 159.18°W and latitude 86.27°N and the south dip pole at longitude 136.59°E and latitude 64.26°S.

In a very general sense the magnetic compass can be considered of *reduced* reliability when the horizontal intensity is less than 0.09 oersted, *erratic* when the field is less than 0.06 oersted, and *useless* when it is less than 0.03 oersted. Figure 3321a and Figure 3321b shows lines of equal horizontal intensity in the north and south polar regions, respectively. However, the effectiveness of the magnetic compass is influenced also by local conditions. A compass on a vessel making a voyage through the islands of the Canadian archipelago has been reported to give fair indication of direction in certain small areas where the horizontal intensity is less than 0.02 oersted, yet to be useless at some places where the horizontal intensity is greater than 0.04 oersted.

Despite its various limitations, the magnetic compass is a valuable instrument in much of the polar regions, where the gyrocompass is also of reduced reliability. With careful

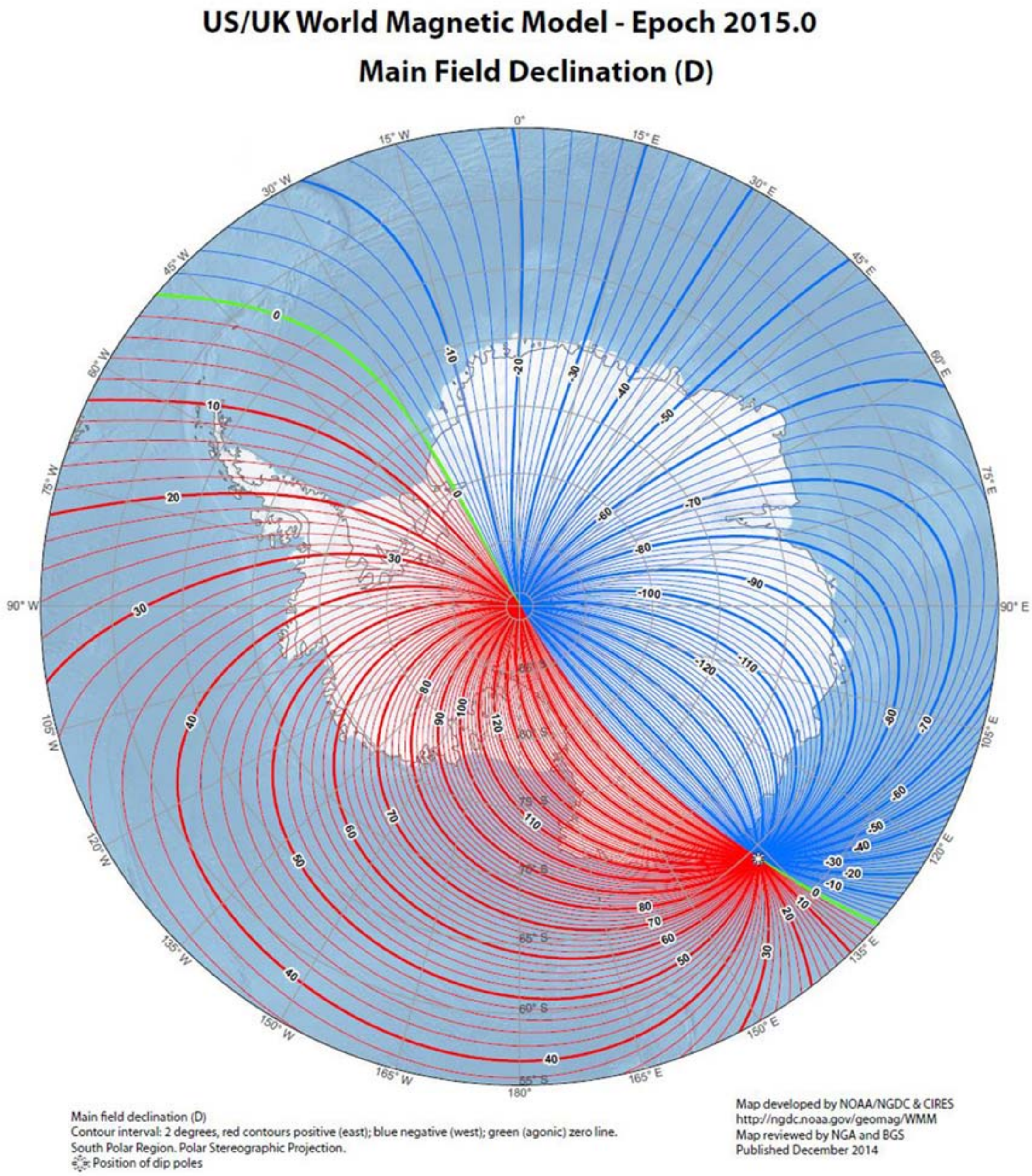

Figure 3321b. Main magnetic field declination for the South pole in 2015.

adjustment, frequent checks, and a record of previous behavior, polar navigators can get much useful service from their instruments.

When a compass is subjected to extremely low temperatures, there is danger of the liquid freezing. Sufficient heat to prevent this can normally be obtained from the compass light, which should not be turned off during severe weather.

To learn more about the magnetic poles see the NGA/NOAA World Magnetic Model (WMM) website and model derivation report via the links provided in Figure and Figure.

3322. Gyrocompass

The gyrocompass depends upon the rotation of the earth about its axis. Its maximum directive force is at the equator, where the axis of the compass is parallel to the axis of the earth. As latitude increases, the angle between these two axes increases. At the geographical poles the gyrocompass has no directive force.

The common gyrocompass is generally reliable to latitude 75°N. North of 75°N special care must be taken in checking its accuracy. Even with the compensation given by the latitude corrector on certain makes of compass, the

World Magnetic Model (WMM)

Figure 3321c. World Magnetic Model website https://www.ngdc.noaa.gov/geomag/WMM/limit.shtml

Figure 3321d. Report on the US/UK World Magnetic Model for 2015-2020. https://www.ngdc.noaa.gov/geomag/WMM/data/WMM2015/WMM2015_Report.pdf

gyro continues to lose horizontal force until, north of about 85°N, it generally becomes unusable. At higher latitudes the disturbing effect of imperfections in compass or adjustment is magnified. Latitude adjustment becomes critical. Speed error increases as the speed of the vessel approaches the rotational speed of the earth. Ballistic deflection error becomes large and the compass is slow to respond to correcting forces. Frequent changes of course and speed, often necessary when proceeding through ice, introduce errors which are slow to settle out. The impact of the vessel against ice deflects the gyrocompass, which does not return quickly to the correct reading.

Fiber optic gyros now have an accuracy of 1.5° at 75°N. At 85°N the accuracy is 4.5° and at 89°N the accuracy is 22° degrees. No gyro that measures the earth's rotation will work well at such high latitudes.

Gyrocompass error scales as a function of 1/cos (Latitude), so the error increases and becomes more erratic as the vessel proceeds to higher latitudes. At latitude 75° the gyro error should be determined frequently, perhaps every four hours, by means of celestial bodies when these are available. As the error increases and becomes more erratic, with higher latitude, it should be determined more frequently. In heavy ice at extreme latitudes an almost constant check is desirable. The gyro and magnetic compasses should be compared frequently and a log kept of the results of these comparisons and the gyro error determinations.

Most gyrocompasses may not be provided with a latitude correction setting above 70°N. Beyond this, correction can be made by either of two methods: (1) set the latitude and speed correctors to zero and apply a correction from a table or diagram obtainable from the manufacturer of the compass, or (2) use an equivalent latitude and speed setting. Both of these methods have proved generally satisfactory, although the second is considered superior to the first because it at least partly corrects for errors introduced by a change in course. In certain types of gyrocompasses, facilities for their operation in a high latitude mode, up to about 86°N, and as directional gyros, even to the poles, is provided.

The manual for the gyro compass should be consulted before entering higher latitudes. The numerous alterations in course and speed and collisions with ice can have an adverse effect on its accuracy. Therefore, when navigating in the Arctic:

- the ship's position should be cross-checked with other navigation systems, such as electronic position fixing devices, where course history could be compared with course steered (allowing for wind and current); and
- the gyro error should be checked whenever atmospheric conditions allow, by azimuth or amplitude.

Since most modern vessels use integrated digital navigation systems, an incorrect ship heading may cause erroneous position estimates if using radar fixes (with bearings having the same error as the gyrocompass). This was a factor in the *SS HANSEATIC* grounding in 1996 in the Canadian Arctic.

3323. Distance and Direction in Ice

In ice-free waters, distance or speed is determined by the installed GNSS and Electronic Chart Display and Information System (ECDIS), or Voyage Management System (VMS). As a backup, some form of log or engine revolution counter may be used as in non-polar operations, but there are some additional error sources. In the presence of ice, however, most logs are inoperative or inaccurate due to clogging by the ice. Engine revolution counters are not accurate speed indicating devices when a ship is forcing its way through ice. With experience, one can estimate the speed in relation to ice, or a correction can be applied to speed by engine revolution counter. However, these methods seldom provide desired accuracy.

If ranges and bearings of a land feature can be determined either visually or by radar, course and speed of the vessel ·or distance traveled over the ground can be determined by tracking the landmark and plotting the results. The feature used need not be identified. Ice can be used if it is grounded or attached to the shore. Course and speed or distance through the water can be approximately determined by tracking a floating iceberg or other prominent floating ice feature. However, an error may be introduced by this method if the effect of wind and current upon the floating feature is different than upon the ship.

3324. Tide, Current and Wind

In general, tidal ranges are small, and the water in most anchorages is relatively deep, however, most tide tables do not extend into polar regions. NOAA manages a number of tide and current stations on the Alaskan coast. Information on Alaskan tides and currents is therefore available from the NOAA website.

Currents in many coastal areas are strong and somewhat variable. When a vessel is operating in ice, the current is often difficult to determine because of frequent changes in course and speed of the vessel and inaccuracies in the measurement of direction and distance traveled.

In the vicinity of land, and in the whole Antarctic area, winds are variable in direction, gusty, and often strong. Offshore, in the Arctic Ocean, the winds are not strong and are steadier, but ships rarely operate in this area. The wind in polar regions, as elsewhere, has two primary navigational effects upon vessels. First, its direct effect is to produce leeway. When a vessel is operating in ice, the leeway may be different from that in open water. It is well to determine this effect for one's own vessel. The second effect is to produce wind currents in the sea.

3325. Conclusion to Polar Dead Reckoning

Because of the potential for loss of GNSS or other aids for fixing the position of a vessel in polar regions, accurate dead reckoning as a backup is even more important than elsewhere. The problem is complicated by the fact that the elements of dead reckoning, direction and distance, are usually known with less certainty than in lower latitudes. This only heightens the need for keeping the dead reckoning with all the accuracy obtainable. This may usually be accomplished by careful hand plotting on the available paper charts or plotting sheets.

PILOTING

3326. Piloting in High Latitudes

Piloting is associated with proximity to land and shoal water, and is basically no different in high latitudes than elsewhere. Piloting is characterized by an alertness not required when a vessel is far from danger of grounding. Nowhere is this alertness more necessary than in polar regions. Added to the usual reasons for constant vigilance are the uncertainties of charted information and the lack of detail, as discussed in Section 3311. Navigators should review *Sailing Directions Pub 180 Planning Guide Arctic Ocean* for tide, current and other piloting information (see Section 3333), along with other nations' sailing directions if available.

3327. Landmarks

Natural landmarks are plentiful in some areas, but their usefulness is restricted by the difficulty in identifying them, or locating them on the chart. Along many of the coasts the various points and inlets bear a marked resemblance to each other. The appearance of a coast is often very different when many of its features are obfuscated by a heavy covering of snow or ice than when it is ice-free.

3328. Bearings

Bearings are useful, but have limitations. When bearings on more than two objects are taken, they may fail to intersect at a point because the objects may not be charted in their correct relation to each other. Even a point fix may be considerably in error geographically if all of the objects used are shown in correct relation to each other, but in the wrong position on the earth. However, in restricted waters it is usually more important to know the position of the vessel relative to nearby land and shoals than its latitude and longitude. The bearing and distance of even an unidentified or uncharted point are valuable.

When a position is established relative to nearby landmarks, it is good practice to use this to help establish the identity and location of some prominent feature a considerable distance ahead, so that this feature, in turn, can be used to establish future positions.

In high latitudes it is not unusual to make use of bearings on objects a considerable distance from the vessel. Because of the rapid convergence of the meridians in these areas, such bearings are not correctly represented by straight lines on a Mercator chart. Additionally, as previously noted, bearing accuracy may be degraded at higher latitudes. If this projection is used, the bearings should be corrected in the same manner that radio bearings are corrected, since both can be considered great circles. Neither visual nor radio bearings are corrected when manually plotted on a Lambert conformal or polar stereographic chart.

3329. Soundings

Soundings are so important in polar regions that echo sounders are customarily operated continuously while the vessel is underway. It is good practice to have at least two such instruments, preferably those of the recording type and having a wide flexibility in the range of the recorder. Since depth of water is a primary consideration to avoid grounding, a constant watch should be maintained to avoid unobserved shoaling.

Polar regions have relatively few shoals, but in some areas, notably along the Labrador coast, a number of pinnacles and ledges rise abruptly from the bottom. These constitute a real danger to vessels, since they are generally not surrounded by any apparent shoaling. In such an area, or when entering an unknown harbor or any area of questionable safety, it is good practice to send one or more small craft ahead with portable sounding gear.

In very deep water, of the order of 1,000 meters or more, the echo returned from the bottom is sometimes confused by the sound of ice coming in contact with the hull, but this is generally not a problem when the bottom is close enough to be menacing.

If a ship becomes **beset** by ice, so that steerage way is lost and the vessel drifts with the ice, it may be in danger of grounding as the ice moves over a shoal. Hence, it is important that soundings be continued even when beset. If necessary, a hole should be made in the ice and a hand lead used. A vessel with limited means for freeing itself may prudently save such means for use only when there is danger of grounding.

Useful information on the depth of water in the vicinity of a ship can sometimes be obtained by watching the ice. A stream of ice moving faster than surrounding ice, or a stretch of open water in loose pack ice often marks the main channel through shoal water. A patch of stationary ice in the midst of moving ice often marks a shoal.

Knowledge of earth formations may also prove helpful. The slope of land is often an indication of the underwater gradient. Shoal water is often found off low islands, spits, etc., but seldom near a steep shore. Where glaciation has occurred, the moraine deposits are likely to have formed a bar some distance offshore. Submerged rocks and pinnacles are more likely to be encountered off a rugged shore than near a low, sandy beach.

3330. Anchorage

Because good anchorages are not plentiful in high latitudes, there is an understandable temptation to be less demanding in their selection. This is dangerous practice, for in polar regions some of the requirements are accentuated. The factors to be considered are:

1. *Holding quality of the bottom*. In polar regions a rocky bottom or one with only fair to poor holding qualities is not uncommon. Sometimes the bottom is steep or irregular. Since the nature of the bottom is seldom adequately shown on charts, a wise precaution is to sample the bottom, and sound in the vicinity before anchoring.
2. *Adequate room for swing*. Because high winds are frequent along polar shores, sometimes with little or no warning, a long scope of anchor chain is customarily used. Some harbors are otherwise suitable, but allow inadequate room for swing of the vessel at anchor, or even for its yaw in a high wind. If a vessel is to anchor in an unsurveyed area, the area should first be adequately covered by small boats with portable sounding gear to detect any obstructions.
3. *Protection from wind and sea*. In polar regions protection from wind is probably the most difficult requirement to meet. Generally, high land is accompanied by strong wind blowing directly down the side of the mountains. Polar winds are extremely variable, both in direction and speed. Shifts of 180° accompanied by an increase in speed of more than 50 knots in a few minutes have been reported. It is important that ground tackle be in good condition and that maximum-weight anchors be used. All available weather reports should be obtained and a continuous watch kept on the local weather. Whenever a heavy blow might reasonably be anticipated, the main engines should be kept in an operating condition and on a standby status. Heavy seas are seldom a problem.
4. *Availability of suitable exit in event of extreme weather*. In ice areas it is important that a continuous watch be kept to prevent blocking of the entrance by ice, or actual damage to the vessel by floating ice. However, in an unsurveyed area it may be dangerous to shift anchorage without first sounding the area. It is a wise precaution to do this in advance. Unless the vessel is immediately endangered by ice, it is generally safer to remain at anchor with optimum ground tackle and use of engines to assist in preventing dragging, than to proceed to sea in a high wind, especially in the presence of icebergs and growlers, and particularly during darkness.
5. *Availability of objects for position determination*. The familiar polar problem of establishing a position by inaccurately charted or inadequately surveyed landmarks is accentuated when an accurate position is desired to establish the position of an anchor. Sometimes a trial and error method is needed, and it may be necessary to add landmarks located by radar or visual observation. Because of chart inadequacy, the suitability of an anchorage, from the standpoint of availability of suitable landmarks, cannot always be adequately predicted before arrival.

An unsurveyed harbor should be entered with caution at slow speed, with both the pilot house and engine room watch-standers alerted to possible radical changes in speed or course with little or no warning. The anchor should be kept ready for letting go on short notice and should be adequately attended. An engine combination providing full backing power should be maintained.

3331. Sailing Directions

Sailing directions for high latitudes contain a wealth of valuable information acquired by those who have previously visited the areas. However, since high latitudes have not been visited with the frequency of other areas, and since these areas may have inadequate surveys, the sailing directions for polar areas are neither as complete nor as accurate as for other areas, and information on unvisited areas is completely lacking. Until traffic in high latitudes increases and the sailing directions for these areas incorporate the additional information obtained, unusual caution should accompany their use. Each vessel that enters polar regions can help correct this condition by recording accurate information and sending it to the National Geospatial-Intelligence Agency (NGA) or its counterpart in other countries. The latest edition of *Sailing Directions, Publication 180 Arctic Ocean*, should be on board for any mariners planning polar operations. *Sailing Directions* are available online via the link provided in Figure 3331a

For additional information on the Arctic and ice navigation in Canadian waters see the link provided in Figure 3331b.

Figure 3331a. Sailing Directions (Planning Guides) https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0011

Ice Navigation in Canadian Waters

Figure 3331b Ice Navigation in Canadian Waters. http://www.ccg-gcc.gc.ca/folios/00913/docs/ice-navigation-dans-les-galces-eng.pdf

ELECTRONICS AND POLAR NAVIGATION

3332. Propagation

In general, radio wave propagation in high latitudes follows the same principles that apply elsewhere, as described in Chapter 21. However, certain anomalous conditions occur, and although these maybe imperfectly understood, and experience to date has not always seemed consistent, there is much information that has been established. An understanding of these conditions is important if maximum effective use is to be made of electronics in high latitudes. Such anomalous conditions are discussed in Chapters 21 and 24.

3333. Radar

In polar regions, where fog and long periods of continuous daylight or darkness reduce the effectiveness of both celestial navigation and visual piloting, and where other electronic aids are generally not available, radar is particularly valuable. Its value is further enhanced by the fact that polar seas are generally smooth, resulting in relatively little oscillation of the shipborne antenna. When ice is not present, relatively little sea return is encountered from the calm sea. In general, Arctic or cold conditions do not affect the performance of radar systems. Occasionally weather conditions may cause ducting, which is the bending of the radar beam because of a decline in moisture content in the atmosphere. This effect may shorten or lengthen target detection ranges, depending on the severity and direction of the bending. A real problem with radar in the Arctic concerns interpretation of the screen for purposes of position fixing. Problems encountered with position fixing arise from either mistaken identification of shore features or inaccurate surveys. Low relief in some parts of the Arctic make it hard to identify landmarks or points of land. Additionally, ice piled up on the shore or fast ice may obscure the coastline. For this reason radar bearings or ranges should be treated with more caution than measurements in southern waters. Visual observations are always preferable. Sometimes it is possible to fix the position of grounded icebergs and then to use the iceberg for positioning further along the track, if performed with caution.

Large areas of the Arctic have not yet been surveyed to the same standards as areas further south, and even some of the more recently produced charts are based on aerial photography. To decrease the possibility of errors, three lines (range, or less preferably bearings) should always be used for positions. Fixes using both sides of a channel or lines from two different survey areas should be avoided. Because of potential problems, fixes in the Arctic should always be compared with other information sources, such as electronic positioning systems.

However, certain limitations affect the use of radar in polar regions. Similarity of detail along the polar shore is even more apparent by radar than by visual observation. Lack of accurate detail on charts adds to the difficulty of identification. Identification is even more of a problem when the shoreline is beyond the radar horizon and accurate contours are not shown on the chart. When an extensive ice pack extends out from shore, accurate location of the shoreline is extremely difficult.

Good training and extensive experience are needed to interpret accurately the returns in polar regions where ice may cover both land and sea. A number of icebergs close to a shore may be too close together to be resolved, giving an altered appearance to a shoreline, or they may be mistaken for off-lying islands. The shadow of an iceberg or pressure ridge and the lack of return from an open lead in the ice may easily be confused. Smooth ice may look like open water. In making rendezvous, one might inadvertently close on an iceberg instead of a ship.

As with visual bearings, radar bearings need correction for convergency unless the objects observed are quite close to the ship.

3334. Electronic Charts

US government produced charts use the WGS-84 Datum and ellipsoid to match the output of the GPS system, so use of any voyage management product that employs both NGA chart products and GPS will not have a datum mismatch. The use of non-US government charts with GPS are a potential problem and the prudent navigator will ensure that the datums of the chart products match, as older products may still use local datums. Russian charts are based on the Krasovsky ellipsoid (Pulkova-42/SK-42). There are some reports that a 100-meter difference may exist in each axis between WGS-84 and Pulkova-42 along the Siberian coast.

3335. Inertial Navigation Systems

Modern military inertial navigation systems (INS) are designed to operate up to the North pole. The use of transverse coordinate systems (described in Section 3314) are typically required as the vessel reaches the very high latitudes, typically above about 85°N. Navigators must ensure that the INS is shifted to this mode and all understand the output of the information. Commercial INS may also function adequately at higher latitudes, but navigators should confirm their performance specification prior to entering the Arctic.

When operating in the Arctic, ships equipped with inertial navigation systems (INS) are required to switch to Transverse Mode to keep the INS solution from degrading when tangents approach zero and to make heading more useful. Transverse Mode is an alternative coordinate system which puts the virtual pole at the normal equator. Heading, Velocity, and Position all change to Transverse Heading (THD), Transverse North and East Velocity (TNV/TEV), and Transverse Lat/Lon (TLT/TLN) when in Transverse Mode.

Military marine INS are designed to function at 90° N. The AN/WSN-7A RLGN has been successfully operated in the Arctic, and at the North Pole (using transverse mode) under a variety of conditions without faults, and it is expected that all future military INS will have similar capabilities.

3336. Global Navigation Satellite Systems (GNSS)

Global satellite navigation systems (GPS, GLONASS, Gallileo, Beidu), are particularly useful in the Arctic because of the scarcity of aids of shorter range. Such short range aids as may be in existence are subject to damage or failure by ice or storms, or other causes. Ice and storm damage may be widespread and require considerable time to repair. Isolated damage may exist for a long time without being discovered and reported.

Some limitations of GNSS must be understood. Since the fielded GNSS are in orbit planes that are at an angle to the equator, GNSS will appear at reduced elevations. For example, GPS has 55 degree orbit planes, thus no satellite altitude higher than 35° degrees will be visible at the North pole. Galileo is similar at 56 degrees, but GLONASS is slightly better with a 65 degree orbit plane.

Because of GNSS receiver mask angles, lower altitude satellites may be removed from calculations; thus, there may be fewer satellites available to the navigator at any given time. Navigators may need to adjust altitude mask angle on receivers to increase number of available satellites, although this might add some increased uncertainty.

Low elevation angles in polar areas have the additional following impacts:

- low angles are good for the horizontal dilution of precision (HDOP), but bad for the vertical dilution of precision (VDOP)
- poorer altitude accuracy will be obtained
- Higher noise level in observations
- Larger ionospheric effects at lower elevation angles

Navigators must understand that there are sparse monitoring infrastructures by any of the GNSS or RF-based navigations systems including:

- Monitoring capability may be temporarily powered
- Poor real-time communication links
- Poor visibility of geostationary satellites
- Arctic area beyond reach of the Euro Geostationary Navigation Overlay Service (EGNOS) and the Wide Area Augmentation System (WAAS)
- GEO satellites low on horizon, visible only for brief periods
- No IALA differential beacons (300 kHz)
- Most RF communications are subject to ionosphere perturbations

If the datum used by the GPS receiver in calculating latitude and longitude is different from the datum of the chart in use, errors will occur when GPS derived positions are plotted on the chart. GPS receivers can be programmed to output latitude and longitude based on a variety of stored datums. The mariner must always ensure that the GPS position output is synchronized to the electronic or paper chart in use.

When GNSS satellite signals travel through the Earth's atmosphere, they are affected by the media of the RF transmission. In the ionosphere, the electromagnetic signals are affected mainly by free negatively charged electrons. The signals experience code delay and phase advance during the transition through the path.

The size of the effect on navigation is a function of the amount of electrons encountered by the signal, defined as the Total Electron Content (TEC). TEC is roughly correlated with the solar activity. The size of the signal delay is dependent on the frequency, i.e. different for GNSS frequencies. For example, it is reported that the typical signal delay causes an error on GPS L1 pseudo ranges of 5-15 meters during day time and 1-3 meters at night. These numbers are global averages with spatial and temporal variations dependent on the solar activity. In GNSS receivers and positioning algorithms the ionospheric effect should be handled by ionospheric models along with data collected from different frequencies and locations.

3337. GNSS Antennas

Antennas are another area of concern, as they can become ice fouled preventing reception, and should be deployed as high as possible to avoid multi-path RF reception problems. GNSS RF frequencies have reduced penetration power in water or ice.

3338. GPS Augmentation Systems

GPS receivers may have the ability to use augmentation systems, which can be either space-based augmentation systems (SBAS), such as Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), and Multi-functional Satellite Augmentation System (MSAS), or terrestrial based augmentation systems like USCG's Differential GPS (DGPS).

For the SBAS systems, GPS correction data is transmitted to navigation users via geostationary satellites (GEO) which are located in the geostationary orbit at the Equator. Thus, the satellites are visible very low on the horizon at high latitudes. SBAS data reception can be often noisy and unreliable, and north of 81° N the satellites are not visible at all. The quality of the correction information is a function of the relative position of the reference station to the vessel used to calculate the corrections. Ground stations are being added. There are also ground stations for EGNOS at Jan Mayen Island and Svalbard Island, and corrections may be available in the Barents Sea from Eurofix. Mariners should consult the respective provides for reference station coverage and estimated accuracy for the intended area of operations.

SBAS suffer by the same limitations caused by ionospheric activity as satellite based positioning and navigation systems. In situations with increased ionospheric activity where ionospheric SBAS corrections really are needed for the EGNOS or WAAS user, the transmission of corrections might be disrupted by ionospheric perturbations.

It is reported that DGPS is also available along the Northern Sea Route (NSR), while there are no known DGPS stations along the Northwest Passage (NWP).

3339. Loran / CHAYKA

At present there is no LORAN coverage available in the Arctic. There is Russian CHAYKA coverage (Russian equivalent to LORAN) in the western part of the NSR, but a CHAYKA receiver must be employed.

3340. Radio Beacons

Other electronic aids exist in parts of the Arctic, particularly along the NSR of Russia. As of 2013, 47 radio beacons were reported along the NSR. Two types are reported to be in use, one with a range of 100 nm and the other with a range of 150 nm. It is also reported at there are radar reflectors along the NSR coast.

3341. Sonar

Sonar is useful primarily for detecting ice, particularly growlers. Since approximately 50%-85% of the ice is under water, its presence can sometimes be detected by sonar when it is overlooked by radar or visual observation.

CELESTIAL NAVIGATION

3342. Celestial Navigation in High Latitudes

Of the various types of navigation, celestial is perhaps least changed in polar regions. However, certain special considerations are applicable. Because of the limitations of other forms of navigation, as discussed earlier in this chapter, celestial navigation provides the principal means of determining geographical position. However, as indicated in Section 3328, position relative to nearby dangers is usually of more interest to the polar navigator than geographical position. Since ships in high latitudes are seldom far from land, and since celestial navigation is attended by several limitations, discussed in Section 3343, its use in marine navigation is generally confined to the following applications:

1. Navigation while proceeding to and from polar regions;
2. Verifying the accuracy of dead reckoning;
3. Verifying the accuracy of charted positions of landmarks, shoals, etc.; and,
4. Providing a directional reference, either by means of a celestial compass or by providing a means of checking the magnetic or gyrocompass.

Although its applications are limited, celestial navigation is important in high latitudes. Application 3 above, and application 4, even more so, can be of great value to the polar navigator.

3343. Celestial Observations

The best celestial fixes are usually obtained by star observations during twilight. As the latitude increases, these periods become longer, providing additional time for observation. But with this increase comes longer periods when the sun is just below the horizon and the stars have not yet appeared. During this period, which in the extreme condition at the pole lasts for several *days*, no celestial observations may be available. The moon is sometimes above the horizon during this period and bright planets, notably Venus and Jupiter, may be visible. With practice, the brighter stars can be observed when the sun is 20° to 30° below the horizon.

Beyond the polar circles the sun remains above the horizon without setting during part of the summer. The length of this period increases with latitude. At Thule, Greenland, about 10° inside the Arctic Circle, the sun remains above the horizon for four months. During this period of continuous daylight the sun circles the sky, changing azimuth about 15° each hour. A careful observation, or the average of several observations, each two hours provides a series of running fixes. An even better check on position is provided by making hourly observations and establishing the most probable position at each observation. Sometimes the moon is above the horizon, but within several days of the new or full phase it provides lines of position nearly parallel to the sun lines and hence of limited value in establishing fixes.

During the long polar night the sun is not available and the horizon is often indistinct. However, the long twilight, a bright aurora, and other sources of polar light (Section 3305) shorten this period. By adapting their eyes to darkness, some navigators can make reasonably accurate observations throughout the polar night. The full moon in winter remains above the horizon more than half the time and attains higher altitudes than at other seasons.

In addition to the long periods of darkness in high latitudes, other conditions are sometimes present to complicate the problem of locating the horizon. During daylight the horizon is frequently obscured by low fog, frost smoke, or blowing snow, yet the sun may be clearly visible. Hummocked sea ice is sometimes a problem, particularly at low heights of eye. Nearby land or an extensive ice foot can also be troublesome. Extreme conditions of abnormal refraction are not uncommon in high latitudes, sometimes producing false horizons and always affecting the refraction and dip corrections.

Because of these conditions, it is advisable to be provided with an artificial horizon sextant (see Section 1415). This instrument is generally not used aboard ship because of the excessive acceleration error encountered as the ship rolls and pitches. However, in polar regions there is generally little such motion and in the ice there may be virtually none. Some practice is needed to obtain good results with an artificial-horizon sextant, but these results are sometimes superior to those obtainable with a marine sextant, and when some of the conditions mentioned above prevail, the artificial-horizon sextant may provide the only means of making an observation. Better results with this instrument can generally be obtained if the instrument is hung from some support, as it generally is when used in aircraft.

An artificial horizon, even an improvised one, (Section 1414) can sometimes be used effectively as by placing heavy lubricating oil in a bucket.

It is sometimes possible to make better observations by artificial-horizon sextant or artificial horizon from a nearby cake of ice than from the ship. Clouds and high fog are frequent in high latitudes, but it is not uncommon, particularly in the Antarctic, for the fog to lift for brief periods, permitting an alert navigator to obtain observations.

As the latitude increases, an error of time has less effect upon altitude. At the equator an error of 4 seconds in time may result in an error in the location of the position line of as much as 1 mile. At latitude 60° a position error of this magnitude cannot occur unless the timing error is 8 seconds. At 70° nearly 12 seconds are needed, and at 80° about 23 seconds are needed for such a position error.

Polaris is of diminished value in high northern latitudes because of its high altitude. At high latitudes the second correction to observed altitude (al) becomes greater. The almanac makes no provision for applying this beyond latitude 68°. Bodies at high altitudes are not desirable for azimuth determination, but if Polaris is used, the use of the actual azimuth given at the bottom of the Polaris tables of the *Nautical Almanac* is of increased importance because of its larger variation from 000° in high latitudes. No azimuth is provided beyond latitude 65°.

In applying a sextant altitude correction for dip of the horizon, one should use height of eye *above the ice at the horizon*, instead of height above water. The difference between ice and water levels at the horizon can often be estimated by observing ice near the vessel.

3344. Low-Altitude Observations

Because of large and variable refraction at low altitudes, navigators customarily avoid observations below some minimum, usually 5° to 15°, if higher bodies can be observed. In polar regions low-altitude observations are often the only ones available. The sun, moon, and planets remain low in the sky for relatively long periods, their diurnal motion being nearly horizontal. The only lower limit is that imposed by the horizon itself. In fact, good observations can sometimes be made without a sextant by noting the time at which either the upper or lower limb is tangent to the horizon. To such an observation sextant altitude corrections are applied as for a marine sextant without an index correction.

If a bubble or other artificial-horizon sextant is used, corrections are made as for higher altitudes, being careful to use the refraction value corrected for temperature, or to make a separate correction for air temperature. In addition, a correction for atmospheric pressure (Table 24) is applied if of sufficient size to be of importance.

3345. Abnormal Refraction and Dip

Tables of refraction correction are based upon a standard atmosphere. Variations in this atmosphere result in changes in the refraction, and since the atmosphere is seldom exactly standard, the mean refraction is seldom the same as shown in the tables. Variations from standard conditions are usually not great enough to be troublesome.

In polar regions, however, it is normal for the atmosphere to differ considerably from the standard, particularly near the surface. This affects both refraction and dip. Outside polar regions, variations in refraction seldom exceed 2' to 3', although extreme values of more than 30' have been encountered. In polar regions refraction variations of several minutes are not uncommon and an extreme value of about 5° has been reported. This would produce an error of 300 miles in a line of position. The sun has been known to rise as much as ten days before it was expected.

Most celestial observations in polar regions produce satisfactory results, but the high-latitude navigator should be on the alert for abnormal conditions, since they occur more often than elsewhere, and have greater extreme values. A wise precaution is to apply corrections for air temperature (Table 27) and atmospheric pressure (Table 28), particularly for altitudes of less than 5°.

Abnormal dip affects the accuracy of celestial observations equally at any altitude, if the visible horizon is used. Such errors may be avoided by using any one of four methods:

1. The artificial-horizon sextant may be used, as indicated in Section 3343.
2. When stars are available, three stars may be observed at azimuth intervals of approximately 120°, (or four at 90° intervals, five at 72°, etc.). Any error in dip *or refraction* will alter the size of the enclosed figure, but will not change the location of its center unless the dip or refraction error varies in different directions. The stars should preferably be at the same altitude.
3. The altitude of a single body may be observed twice, facing in opposite directions. The sum of the two readings differs from 180° by twice the sum of the index and dip corrections (also personal and instrument corrections, if present). This method assumes that dip is the same in both directions, an assumption that is usually approximately correct. Also, the method requires that the arc of the sextant be sufficiently long and the altitude of the body sufficiently great to permit observation of the back sight in the opposite direction. In making such observations, it is necessary that allowance be made for the change of altitude between readings. This may be done by taking a direct sight, a back sight, and then another direct sight at equal intervals of time, and using the average of the two direct sights.
4. A correction for the difference between air and sea temperatures may be applied to the sextant altitude. This will often provide reasonably good results. However, there is considerable disagreement in the manner in which temperature is to be measured, and in the factor to use for any given difference. Therefore, the validity of this correction is not fully established.

There is still much to be learned regarding refraction and even with all known precautions, results may occasionally be unsatisfactory.

3346. Sight Reduction

Sight reduction in polar regions is virtually the same as elsewhere. Computation can be made by nearly any method, or by use of common computer applications. One special method of considerable interest is applicable only within about 5° of the pole, a higher latitude than is usually attainable by ships. This is the method of using the pole as the assumed position. At this point the zenith and pole coincide and hence the celestial equator and celestial horizon also coincide, and the systems of coordinates based upon these two great circles of the celestial sphere become identical. The declination is computed altitude, and GHA replaces azimuth. A "toward" altitude intercept is plotted along the upper branch of the meridian over which the body is located, and an "away" intercept is plotted in the opposite direction, along the lower branch. Such a line or its AP is advanced or retired in the usual manner. This method is a special application of the meridian altitude sometimes used in lower latitudes. Beyond the limits of this method the meridian altitude can be used in the usual manner without complications and with time of transit being less critical. However, Table 24, for reduction to the meridian, extends only to latitude 60°.

3347. Manual Plotting of LOPs

Lines of position from celestial observations in polar regions are plotted as elsewhere, using an assumed position, altitude intercept, and azimuth. If a paper Mercator chart is used, the error introduced by using rhumb lines for the azimuth line (a great circle) and line of position (a small circle) is accentuated. This can be overcome by using a chart on a more favorable projection.

If a chart with nonparallel meridians, such as the Lambert conformal, is used, the true azimuth should be plotted by protractor or plotter and measured at the meridian of the assumed position. On a chart having a grid overprint the true azimuth can be converted to grid azimuth, using the longitude of the assumed position, and the direction measured from any grid line. This method involves an additional step, with no real advantage.

Lines of position from high-altitude observations, to be plotted as circles with the geographical position as the center, should not be plotted on a paper Mercator chart because of the rapid change of scale, resulting in distortion of the circle as plotted on the chart.

Lines of position are advanced or retired as in any latitude. However, the movement of the line is no more accurate than the estimate of the direction and distance traveled, and in polar regions this estimate may be of less than usual accuracy. In addition to the problem of estimated direction of travel, the polar navigator may encounter difficulty in accurately plotting the direction determined. If an accurate gyrocompass is used, the ship follows a rhumb line, which is accurately shown only on a Mercator chart. If a magnetic compass is used, the rapid change in variation may be a disturbing factor. If the ship is in ice, the course line may be far from straight.

Because of the various possible sources of error involved, it is good practice to avoid advancing or retiring lines for a period longer than about two hours. When the sun is the only body available, best results can sometimes be obtained by making an observation every hour, retiring the most recent line one hour and advancing for one hour the line obtained two hours previously. The present position is then obtained by dead reckoning from the running fix of an hour before. Another technique is to advance the one or two previous lines to the present time for a running fix. A third method is to drop a perpendicular from the dead reckoning or estimated position to the line of position to obtain a new estimated position, from which a new dead reckoning plot is carried forward to the time of the next observation. A variation of this method is to evaluate the relative accuracy of the new line of position and the dead reckoning or estimated position run up from the previous position and take some point between them, halfway if no information is available on which to evaluate the relative accuracies. None of these techniques is suitable for determining set and drift of the current.

3348. Rising, Setting and Twilight

Rising, setting, and twilight data are tabulated in the almanacs to latitude 72°N and 60°S. Within these limits the times of these phenomena are determined as explained in Chapter 17, The Almanacs.

Beyond the northern limits of these tables the values can be obtained from a series of graphs given near the back of the Air Almanac. For high latitudes, graphs are used instead of tables because graphs give a clearer picture of conditions, which may change radically with relatively little change in position or date. Under these conditions interpolation to practical precision is simpler by graph than by table. In those parts of the graph which are difficult to read, the times of the phenomena's occurrence are themselves uncertain, being altered considerably by a relatively small change in refraction or height of eye. The use of the graphs is explained in Chapter 17, The Almanacs.

SUMMARY

3349. Knowledge of Polar Regions

Operations in polar regions are attended by hazards and problems not encountered elsewhere. Lack of knowledge, sometimes accompanied by fear of the unknown, has prevented navigation in these areas with the same confidence that is pursued in more familiar areas. As experience in high latitudes has increased, much of the mystery surrounding these areas has been dispelled, and operations have become more predictable.

Before entering polar regions, navigators will do well to acquaint themselves with the experience of those who have preceded them into the areas and under the conditions they anticipate. This information can be found in the growing literature composed from the accounts of explorers, reports of previous operations in high latitudes, articles in professional journals, and several books on operations in polar regions. Some of it is published in various volumes of sailing directions.

The search for knowledge should not be confined to navigation. The wise polar navigator will seek information on living conditions, survival, geography, ice, climate and weather, and operational experience of others who have been to the same area. As elsewhere, knowledge and experience are valuable. The Encyclopedia of the Arctic (3 Volumes), Mark Nuttall Editor is the reference for all things "arctic" from Archaeology to Zagoskin (ie Lavrentii Zagoskin), and includes chapters on weather, wildlife, politics, history, oceanography, environment and indigenous peoples.

3350. Planning

Planning, important in any operation, is vital to the success of polar navigation. The first step to adequate planning is the acquisition of full knowledge, as discussed in Section 3349. No item, however trivial, should escape attention. The ship should be provided with all the needed charts, publications, and special navigational material. All available data and information from previous operations in the area should be studied. Key personnel should be adequately instructed in polar navigation prior to departure or while enroute to the polar regions. Forecasts on anticipated ice and weather conditions should be obtained before getting under way. All equipment should be in top operating condition. All material should be carefully inspected for completeness and accuracy. The navigator should make certain that all items of equipment are familiar to those who will use them. This is particularly true of items not generally used at sea, such as charts on an unfamiliar projection, or a bubble sextant. Do not assume anything that can be known. Successful polar navigation depends on adequate and thorough advanced planning and preparation.

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