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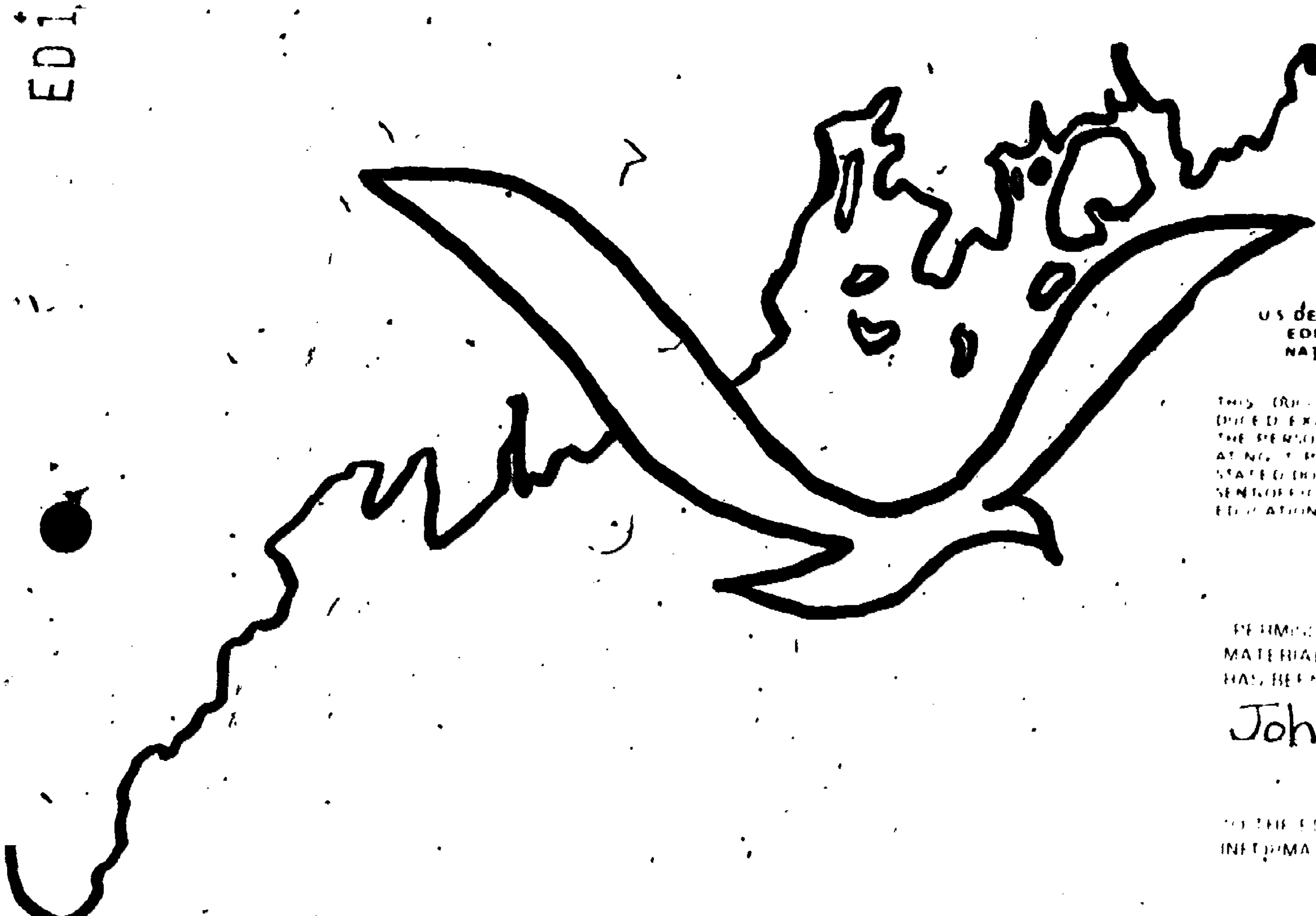
ABSTRACT

This guide provides student practice problems which use the procedures of ship navigators to reinforce the skills of mathematics learned in the secondary school and which seek to provide examples of the application of mathematical concepts. Along with the practice problems, teacher background material is provided briefly in the body of the unit. More detailed explanations are provided in the appendices. A reference section is included. (RE)

NNMEP / NORTHERN NEW ENGLAND MARINE EDUCATION PROJECT



NAVIGATION

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Northern New England Marine Education Project

College of Education

University of Maine at Orono

Orono, Maine

NAVIGATION

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The College of Education, University of Maine

Title: NAVIGATION

*Marine Concept: 4.11

4. Man is part of the marine ecosystem.

   4.1 The marine environment has affected the course of history and the development of human cultures.

      4.11 The oceans have served as routes for the dispersal of human populations and for commercial transport.

Grade Level: Secondary (variable)

Subject: Mathematics

Class Periods: Variable

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TABLE OF CONTENTS

TABLE OF CONTENTS - continued

INTRODUCTION

Over the past three or four years, a growing number of teachers have become interested in presenting some topics in their classes with focuses relating to the marine environment. This growth can be seen by the significant increase in membership in such organizations as the National Marine Education Association. Interested secondary mathematics teachers can provide an occasional nautical focus for their students by drawing upon the practices of ships' navigators for the student practice problems.

Practical examples for student practice of newly acquired arithmetic and mathematical skills increase student interest and understanding. They can also provide answers to student questions regarding the applicability of apparently obscure mathematical concepts. Practices utilized by navigators can be the source of many interesting practical examples for students in secondary math courses from basic algebra to spherical trigonometry. Students will be impressed to find that the basic procedures they learn are the bases for the navigator of boats from the smallest coastwise types to the largest crude carriers, and of airplanes from the lightest private planes to the heaviest airliners.

Students must learn some basic vocabulary in order to make the exercises meaningful and realistic. The amount of vocabulary necessary depends primarily upon the mathematical skill level being taught. For example, first year algebra students being given dead-reckoning problems as a variant of distance, rate, and time problems would need to learn only a very few new terms to keep their problems consistent with those addressed by the coastwise pilot. On the other hand, students working with the resolution of celestial spherical triangles in a more advanced course would have to develop a fairly thorough understanding of the coordinate systems used on both the terrestrial and celestial spheres and a number of labels and symbols peculiar to the celestial navigator.

Across this continuum of complexity there exists an opportunity for mathematics teachers and geography teachers to conspire to instill in their students an understanding of the graticule (lines of latitude and longitude) we have constructed for our planet and its importance to those who navigate the expanses of our seas and skies.

Following are some sample problems with solutions for students to try. The processes represented are by no means the only navigational practices which could be used effectively in the classroom. They will, however, serve as good examples of the type of material teachers might use at different levels of school math skill.

Teacher background material is presented very briefly and basically in the body of this unit. More detailed explanations are provided in the appendices and authoritative references cited for those with further interest.

DEAD RECKONING

Introduction

Dead, or deduced, reckoning is the most basic of the navigational practices. It involves simply accounting for the speed, direction, and length of time of travel of your vessel to arrive at your deduced position. This position is commonly called the DR position of the vessel and is kept by all navigators. Practically, the navigator keeps track of his speed, direction, and length of time of travel from a known position called a fix. In the examples we use in our exercises, the fix will be established by close proximity of the ship to a known navigational aid or land feature.

Concepts Stressed by the Process

Algebra students will have little trouble dealing with the navigator's distance, rate, and time formula. For most inshore navigation or pilotage, the navigator uses the formula 60D = ST, since he is to be dealing with time expressed in minutes. It is clear that this represents only a minor adaptation to the standard distance, rate, and time formula (D = RT) commonly taught in school mathematics.

Direction Determination

Several different means of measuring and recording direction are discussed in Appendix A. While using this material with your students, use true directions. That is, consider directions of travel as being measured clockwise from true North. True North is easy to locate on a chart or map, since the meridians, or lines of longitude, run true North-South. To determine a true course on a chart, just measure the angle formed between a meridian and the course line. Measure this angle clockwise from North. Several examples are shown below.

Speed

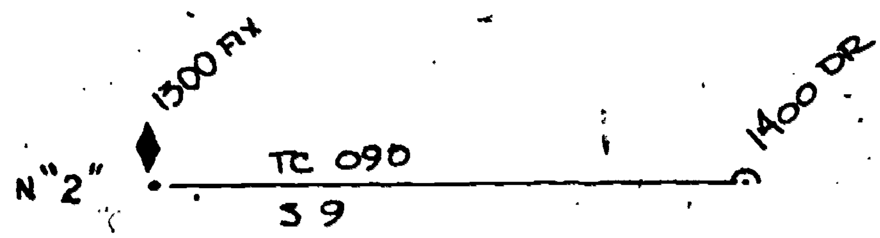
Speed is always expressed in knots, which are nautical miles per hour. You will sometimes hear people talk about knots per hour. This is incorrect usage, unless they happen to be talking about an acceleration, which is unlikely. One nautical mile = 1.15 statute miles. Nautical miles are particularly handy for navigators to work with since 1 nautical mile = 1' of latitude, which can be readily measured from the vertical margin of any chart. Fractions of nautical miles are reported in tenths.

Time

The maritime navigator utilizes hours, minutes, and seconds in his distance computations. As expressed earlier, pilotage work often necessitates the use of minutes alone.

Dead Reckoning - The Process

The actual process of dead reckoning is quite simple. If we are close aboard buoy N "2" at 1300 and proceeding on course of 090° TC at a speed of 9K, we can predict, or deduce, our position at subsequent times. For example, at 1400, one hour later, we will be 9 nautical miles east of N "2". That would be plotted in this manner on a chart.

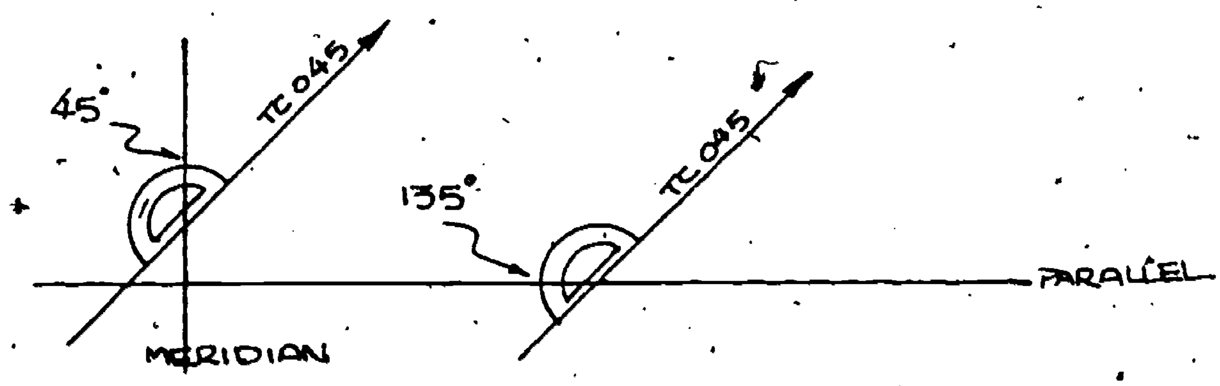


Note that the true course (TC) is printed above the plotted course line and the speed (S) is printed below the course line. The times are labeled not parallel to any line. The 1300 position is labeled the 1300 fix, because our position is known since we're close to the buoy. The 1400 position is labeled 1400 DR since it was arrived at through dead reckoning.

Students can quickly learn these simple conventions and then enjoy solving 60D = ST in order to locate various DR positions along the course line on real or fictitious charts.

The actual measuring of courses on the chart, or plotting of courses on the chart is done using some sort of course protractor, or parallel rules. Parallel rules are simply two rules attached to each other so that moving one will result in moving a line segment parallel to the line segment formed by the stationary leg. (Note the possible use of an example of parallel lines and transversals.) To plot a course, the desired course is found on the compass rose nearest your area and one edge of the parallel rules is laid down to intersect the center of the compass rose and the mark on the circle for the appropriate course. You'll notice that the outer ring of courses is true courses, while the inner ring consists of magnetic courses. The other rule is then moved toward the area in which you want to construct the course line. The parallel rules can be "stepped" across the chart in this manner until you are able to lay down your course line where you want it.

Course protractors are basically just elongated protractors. Some models include gadgets for corrections of variation and deviation, while others do not. Simple school protractors can be used readily, particularly when using true courses. Any meridian or parallel can be used as a base line for the use of a standard protractor. A ruler along the edge of the protractor will make the edge of usable length. When using a parallel line of latitude, remember that your reference line runs east and west and this 90° shift from North must be accounted for in your measurement.



It is often necessary to determine deduced position (DR position) at times other than on the hour, or half hour. These positions can be arrived at through use of the equation, and usually are, but you might like to teach proportions from this frame of reference. For example, how far along the course line would we be in the previous example at 1425, at the same speed (9K)?

$$\frac{9}{60} = \frac{X}{25}$$

Dead Reckoning Sample Problems

Use the sample chart included

1. What is the distance in nautical miles from the black and white buoy "OH" to N"4" marking the channel by Old Man Point?

2. If you are at BW "OH" at 1300, what time will you arrive at N"4" marking the channel to Old Man Point if your boat is sailing at 5 knots? At 7.5 knots? At 6 knots? Would you steer this course directly, or would you make for a different mark first? Why?

3. What is the true course between BW"OH" and N"4" marking the channel to Old Man Point?

4. If you were close aboard whistle buoy "3", what true course would you order to enter the center of the mouth of the inlet by Old Man Point? About how far would you have to travel until you were in the mouth of the river?

5. Using the information in question 4, if you were close aboard whistle "3" at 2200, what time would you expect to arrive in the mouth of the inlet traveling at 9 knots? At 4.5 knots?

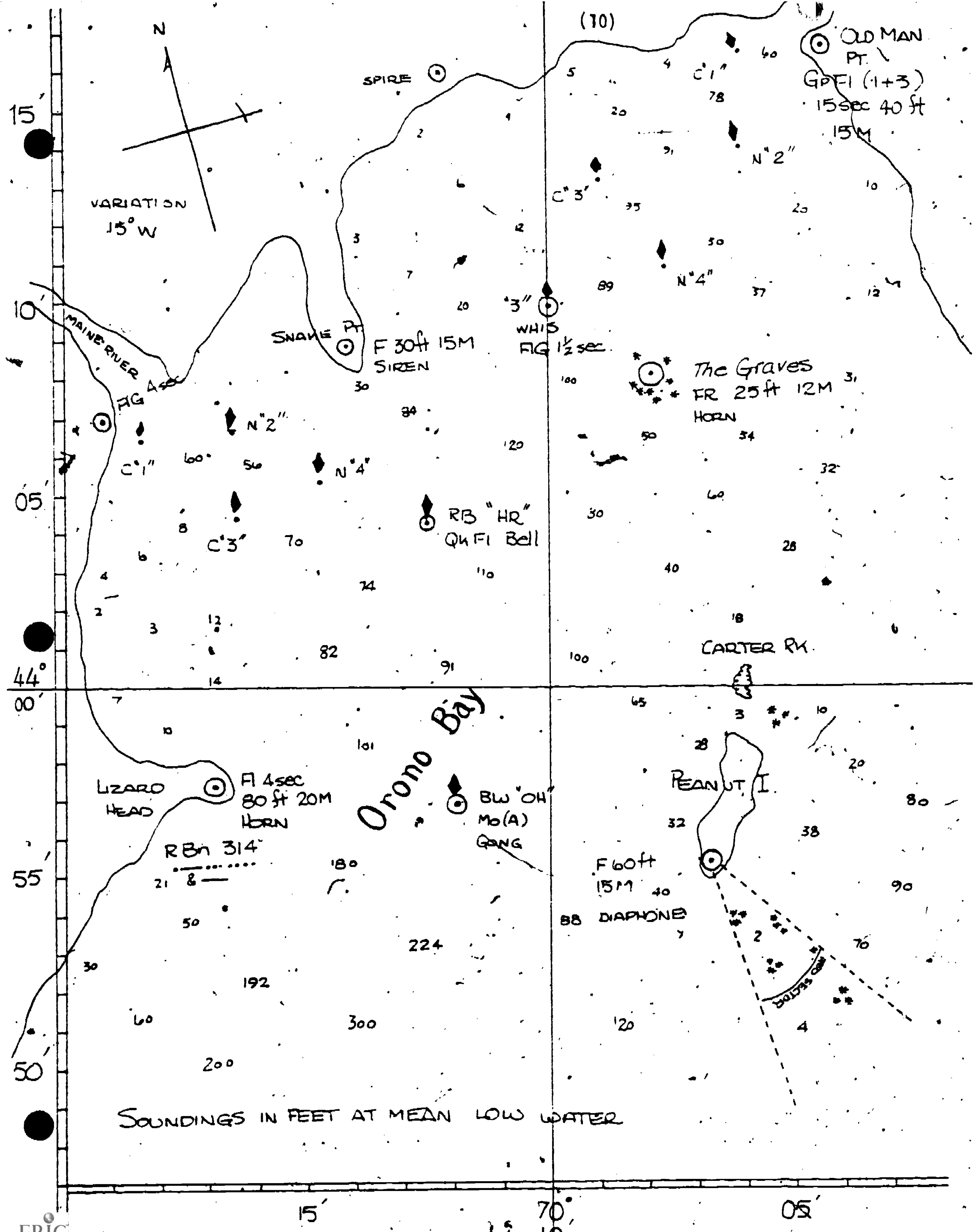
6. You've been sailing all night. Just before sunrise, you sight RB"HR" with virtually no visibility. What true course do you steer to reach the mouth of the Maine River? At 6 knots, what approximate time would you expect to be there? What two buoys would you pass close to?

7. In the above problem, about what time would you expect to be closest to the first of these buoys? To the second?

8. After picking your way in on a foggy night, you find yourself quite close to land and to a lighthouse, which you identify as Peanut Island Light. What true course would you steer to reach Whistle "3"?

9. In the problem above, you depart Peanut Island Light at 0100; what speed must you maintain to arrive at WHIS "3" at approximately 0230? At 0300?

10. Leaving WHIS "3" at 0600 for an offshore fishing trip, you steer true course 180°. You are steaming at 12 knots. What time do you expect to cross latitude 44°00'N?



(70)
N
VARIATION 15° W
SPIRE
OLD MAN PT.
GpFl (1+3) 15 sec 40 ft 15 M
C "1"
N "2"
C "3"
N "4"
"3"
WHIS
FlG 1½ sec
SNAKE PT
F 30ft 15M
SIREN
MAINE RIVER
FlG 4 sec
The Graves
FR 25 ft 12M
HORN
N "2"
C "1"
N "4"
C "3"
RB "HR"
Qk Fl Bell
CARTER RK
Orono Bay
LIZARD HEAD
Fl 4sec
80 ft 20M
HORN
BW "OH"
Mo (A)
GONG
PEANUT I.
F 60 ft
15M
DIAPHONE
RBn 314
SOUNDINGS IN FEET AT MEAN LOW WATER
15'
10
05'
44° 00'
55'
50'
15'
70° 10'
05'

Answers to Sample Problems

1. 9 miles (remember, 1 nautical mile = 1' of latitude; so, measure the distance between the buoys with a pair of dividers and compare it with the latitude scale on the left edge of the chart. The distance is 9' of latitude, or 9 nautical miles)

2. 1448 at 5 knots   60 x 9 = 5 x T; T = 108 minutes. 108 minutes = 1 hour 48 minutes.
$$\begin{array}{r} 1300 \\ +\ 148 \\ \hline 1448 \end{array}$$
1412 at 7.5 knots
1430 at 6 knots
The direct course from "OH" to N"4" leads very close to the rocks at The Graves. You would probably choose to steer for WHIS "3" first.

3. "OH" to N"4" is about 011° true.

4. About 042°; about 9.5 miles.

5. 2303 at 9 knots; 0007 at 4.5 knots.

6. True course 292°; 0605 at 6 knots. You'd pass close to N"4" and N"2".

7. 0515; 0541

8. About 345°

9. 10 knots to arrive at 0230. It's about 15 nautical miles to WHIS "3" from Peanut Island lt., and 0230 is 90 minutes from 0100.
$$60 \times 15 = S \times 90 \qquad \frac{900}{90} = 10 \text{ knots}$$
7.5 knots to arrive at 0300.

10. 0650

Dead Reckoning Problems

These problems are based on NOAA Chart No. 13288 (formerly C & GS 1204), Monhegan Island to Cape Elizabeth. See page for information on buying charts.

1. How far is it from Halfway Rock Light on Webster Rock to R"20 ML" on Mile Ledge off Seguin Island? What is the true course between the two points?

2. If you left Halfway Rock Light sailing at 8 knots, how many minutes would you expect it to be before you were close to R"20 ML"? How many hours and minutes?

3. Using the information in the first two problems, at what time would you expect to reach R"20 ML", if you departed Halfway Rock Light at 1350?

4. A popular Maine yacht race begins off Clapboard Island near Falmouth. The race goes down to Cape Porpoise and then to R"14 M" just west of Monhegan Island. The last long leg is from R"14 M" to Bell "1" which is .6 miles east-southeast of Witch Rock off Cape Elizabeth. (Bell "1" is at lo. 70°09.8' W, l 43°37.1" N) How long is the leg of the race?

5. If you rounded R"14 M" at midnight on the race, what speed would you have to make to reach Bell "1" at 0400?

6. If the next course on the race took you to Gong "3" at the entrance to Hussey Sound, what course would you steer to get there?

7. At what time would you expect to arrive at Gong "3" if you continued traveling at the same speed as your answer in Problem 5? (Assume that you rounded Bell "1" at 0400) At this rate, you'll surely win the event!

8. If you decided to row from Gong R"2" off Pemaquid Neck to BW Bell "HL" of Linnekin Neck, and then straight to the eastern shore of Squirrel Island in Booth Bay, how many miles would you row? What would your first course be?

9. If you leave Gong R"2" at 1200, rowing at 2 knots, what time would you expect to reach BW Bell "HL"?

10. What is your course from BW Bell "HL" to the end of the small point on the eastern shore of Squirrel Island? At 2 knots, what time would you expect to reach the point after leaving BW Bell "HL" at the same time you arrived in Problem 9?

Answers to Dead Reckoning Problems

Based on the Monhegan Island to Cape Elizabeth Chart

1. 17.5 nautical miles. 261° true
2. 131 minutes; 2 hours, 11 minutes
3. 1601
4. 35.3 nautical miles
5. 8.8 knots
6. True course 355°
7. 0419
8. 5.1 nautical miles; 245°
9. 1333
10. 271°; 1433

DETERMINING LATITUDE AND LONGITUDE

Positions at sea and on land in wilderness areas are often best described using the latitude and longitude coordinates of the position. If, for example, you wanted to report your location at sea to a friend in another boat so that he could rendezvous with you, you would locate your position on your chart, and report it to him by radio. To find the latitude and longitude coordinates of a point on the chart, simply construct perpendiculars from the point to the latitude and longitude scales on the margins of the chart. There you can read latitude and longitude to the nearest minute, or you can interpolate between minutes for increased accuracy.

For example, on the accompanying chart, you will see that perpendiculars have been constructed from Snake Point Light to the scales on the margins of the chart. You can see that the latitude of Snake Point Light to the nearest minute is 44° 09'N. Interpolating, you might call the latitude 44° 08.9'N. The longitude measured along the bottom margin is 70° 14' to the nearest minute, while it is 70° 14.2'W if you interpolate.

This hypothetical chart depicts a location in the Northern Hemisphere. You could deduce this from the fact that latitude measure is increasing as you go north. On a chart of the Southern Hemisphere, the opposite would be true, that is, latitudes would increase numerically as you went south. Similarly, this chart represents an area west of the prime meridian as you can tell by the numerical increase in longitude as you proceed west.

No scale of distances is drawn on this chart so that students will learn to equate minutes of latitude with nautical miles. Do not allow them to equate minutes of longitude with nautical miles, since on the Mercator Projection chart, the minutes of longitude decrease in size relative to minutes of latitude as you go away from the equator. The only place that a minute of longitude would equal one nautical mile is at the equator. No compass rose is provided on the chart, but variation information is available in the upper left hand corner.

Problems Determining Latitude and Longitude

These problems are based on the fictitious chart provided with the material.

1. What are the latitude and longitude of Snake Point Light?

2. What are the coordinates (latitude and longitude) of Peanut Island Light?

3. What are the coordinates of Lizard Head Light?

4. What are the coordinates of Old Man Point Light?

5. If you were at WHIS "3" and wanted to sail directly to l 44°00.0'N, lo 70°10.0'W, what course would you have to steer? How far from the whistle is that point?

6. If you sailed 3 miles due west from buoy N "4" off Old Man Point, what would your position be at the end of those 3 miles (latitude and longitude)?

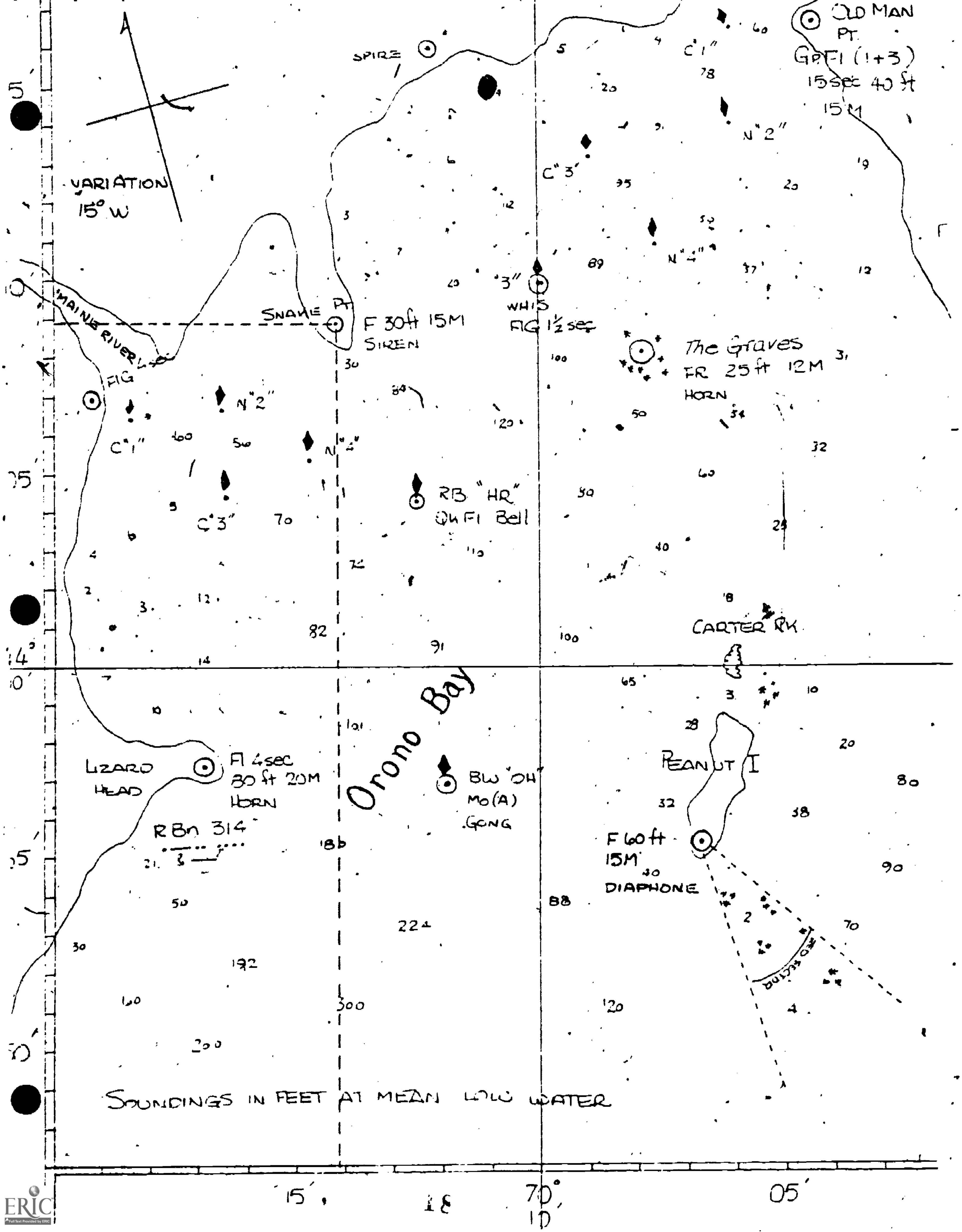
7. If you traveled 5 miles due north from BW "OH" and then turned to a due easterly course and traveled 3 miles, what would your position be?

8. What is the true course and distance from BW "OH" to l 44°05.0'N, lo 70°05.0'W?

9. What is the true course and distance from l 44°05.0'N, lo 70°05.0'W to C "3" off the mouth of Maine River? How long would you have to sail at 7 knots to cover that distance?

10. If you sailed the following courses at 6 knots for the time periods given, what would your location be at the end of these courses? Begin at WHIS "3".

TC	235	Time 1 hr. 10 min.
TC	145	Time 50 min.
TC	250	Time 47 min.


N
VARIATION
15° W
SPIRE
OLD MAN PT
GpFl (1+3)
15sec 40 ft
15M
C "1"
N "2"
C "3"
N "4"
"3"
WHIS
FlG 1½ sec
SNAKE PT
F 30ft 15M
SIREN
MAINE RIVER
FlG
N "2"
C "1"
N "4"
C "3"
The Graves
FR 25 ft 12M
HORN
RB "HR"
QkFl Bell
CARTER RK
Orono Bay
PEANUT I
LIZARD HEAD
Fl 4sec
30 ft 20M
HORN
BW "OH"
Mo(A)
GONG
RBn 314
F 60 ft
15M
DIAPHONE
RED SECTOR
SOUNDINGS IN FEET AT MEAN LOW WATER
15'
70°
10'
05'

Answers to Problems Determining Latitude and Longitude
Based on the included chart.

1. 1 44° 08.9' North; lo 70° 14.2' West (can be rounded to nearest minute)

2. 1 43° 55.4'N; lo 70° 06.8'W

3. 1 43° 57.4'N; lo 70° 16.9'W

4. 1 44° 16.7'N; lo 70° 04.4'W

5. 180°; 10 nautical miles

6. 1 44° 10.9'N; lo 70° 10.0'W

7. 1 44° 01.8'N; lo 70° 09.5'W

8. TC 048°; 11.0 nautical miles

9. TC 268°; 14.5 nautical miles; 124 minutes (2 hrs. 04 min.)

10. 1 43° 58.5'N; lo 70° 14.7'W

Problems Determining Latitude and Longitude

These problems are based on NOAA Chart No. 13288 (formerly C & GS 1204), Monhegan Island to Cape Elizabeth.

1. What are the latitude and longitude of Halfway Rock Light?

2. What are the latitude and longitude (coordinates) of Monhegan Island Light?

3. What are the coordinates of the WPOR radio tower in the Woodfords section of Portland?

4. What are the coordinates of Pemaquid Point Light?

5. If you were at Fuller Rk. Lit. and wanted to sail directly to l 43° 30.0'N, lo 69° 50.0'W, what true course would you steer? What distance would you have to travel?

6. If you traveled 4 miles on a true course of 135° from BW "WB" west of Cape Small, what would your position be at the end of the 4 miles?

7. If you traveled due south (true)(180°) from R "20ML" off Seguin Island, for 9.7 nautical miles and then turned to a due westerly (true)(270°) course, and traveled 14.8 more miles, what would your position be? What navigational aid would you be close to?

8. What is the true course and distance from R"14M" off Monhegan Island to l 43° 40.0'N, lo 69° 30.0'W?

9. What is the true course and distance from l 43° 40.0'N, lo 69° 30.0'N to R"20ML" off Seguin? How long would it take you to travel that course at 8 knots?

10. Beginning at R"20ML", plot the following courses. You are traveling at 12 knots, for the given lengths of time. What would your position be at the end of the last course?

TC	221°	Time 30 min.
TC	300°	Time 30 min.
TC	238°	Time 65 min.

What is the name of the small harbor you've reached?

Solutions to Latitude and Longitude Problems

Based on NOAA Chart No. 13288

1. l 43° 39.3'N; lo 70° 02.2'W

2. l 43° 45.9'N; lo 69° 19.0'W

3. l 43° 39.9'N; lo 70° 16.2'W

4. l 43° 50.2'N; lo 69° 30.4'W

5. TC 180°, distance 11.7 nautical miles

6. l 43° 40.0'N; lo 69° 51.4'W

7. l 43° 31.6'N; lo 70° 05.5'N. R"P". This is a large buoy (40' diameter) that has replaced to "Portland" lightship.

8. TC 226°, 7.6 nautical miles

9. TC 278°, 11.3 nautical miles. Travel time 85 minutes.

10. l 43° 33.0'N; lo 70° 13.3'W, Seal Cove

BEARINGS

A basic piloting skill utilized by navigators of all sized vessels is the taking of bearings on objects with known locations. Taking several nearly simultaneous bearings on different objects and plotting them can result in a fix, which is a reasonably certain plot of your position at that time.

A bearing is taken by noting the direction from you to the object using a compass. Several devices such as the hand bearing compass and pelorus have been developed for taking accurate bearings, but any compass will do.

In the included problems we will discuss only true bearings (See Appendix A) for procedures to be used correcting actual compass bearings. Teaching students about bearings presents a good opportunity to discuss directional reciprocals, since you will plot the reciprocal of the true bearing (TB) from the object toward your position.

In plotting from the known position toward the approximate position of the boat, we are drawing a line of position (LOP). We know that our boat is somewhere along that LOP if we have taken the bearing correctly. You can see that by plotting two or more of these bearings, a fix can be established at the intersection of the LOP's.

When plotting an LOP write the bearing to the object above the line and the time of the bearing below the line.

Bearing Problems

These problems are based on the chart provided with the material.

1. If you were standing at the light on The Graves, what would the bearing of WHIS "3" be? Of RB "HR"? Of Peanut Island Light? Of Old Man Point Light?

2. What is the bearing of The Graves from Snake Point Light?

3. Draw a line of position (LOP) that would represent your position if Peanut Island Light had a bearing of 080° from your boat.

4. What would your latitude and longitude be if you took bearings on The Graves and Snake Point and found The Graves to bear 355° and Snake Point Light to bear 310°?

5. What would your position be if you took bearings on Lizard Head Light and found it to bear 130° and Peanut Island Light had a bearing of 060° at the same time?

Solutions to Bearing Problems.

Based on the chart provided with the material

1. 305°; 237°; 173°; 029°
2. 095°
3. Draw a line from Peanut Island Light toward 260°.
4. l 44° 01.8'N, lo 70° 07.5'N
5. l 43° 51.8'N, lo 70° 11.7'W

APPENDIX A
DIRECTION DETERMINATION

The compass is divided into 360 degrees. These begin at North (000°, 360°) and are counted clockwise with 090° being East, 180° being South, and 270° being West. While the old-timers used to name course by points of the compass, nearly all navigators now use the 360° compass in naming courses. For example, an old fisherman might have steered so'so'east from the harbor to the fishing grounds; today's mariner would be more likely to call the same course 157°.

There are several different measures of direction with which navigators must be familiar. These include true directions, those relative to the graticule, lines of latitude and longitude; magnetic directions, those relative to the magnetic poles of the earth; and compass directions, those relative to the ship's compass. These types of directions, and the factors which separate them will be explained in some detail here for your interest. Changing from one type of direction measurement to the other requires algebraic addition of integers which might make good algebra practice for students.

True directions are those measured relative to the parallels and meridians of the graticule. True courses can only be read directly from gyrocompasses, and these must be set from magnetic compasses using known variations. Many small boat navigators never use true courses, while some use them because any parallel or meridian of the printed graticule on a Mercator Projection Chart can be used for a reference when using true courses.

Since the earth's magnetic poles are not located at the geographic poles, magnetic courses are not the same as true courses. The angular difference between true North and magnetic North at any given location is called variation. It will usually be expressed in degrees, minutes, and tenths of minutes east or west of North. The actual value of variation varies greatly from place to place on the earth's surface. For example, variation is approximately 17°W along the central Maine coast, while it is only 2°W off the Florida coast. Since the earth's magnetic field is slowly moving, this value changes slightly every year. The correct current value of variation for any given area can be found in the center of the compass rose on the chart of the area.

When changing magnetic course to true courses, easterly values for variation are added to the magnetic course to arrive at true courses, and westerly variations are subtracted from magnetic courses to arrive at true courses. For example, a magnetic course of 218° in an area of 17°W variation would represent a true course of 201° (MC - var.W = TC). Converting from true course to magnetic courses, westerly variations are added, while easterly variations are subtracted.

You can see the reason for this in the diagrams. In figure 1, notice that magnetic north is 12° east of true north. Therefore, a course of 030° magnetic, would be 042° true, or 030° + 12° - 042°.

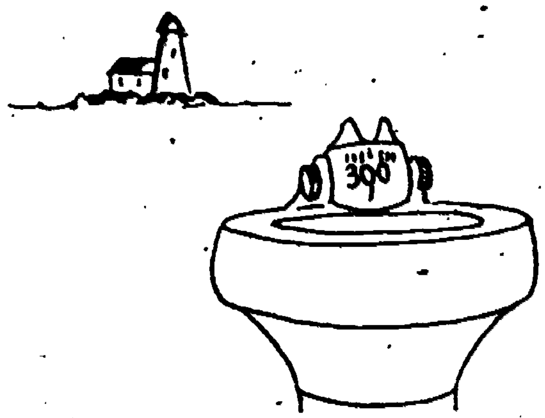
In figure 2, magnetic north is 15° west of true north. You can see that a course of 340° magnetic would be 15° less when expressed as a true course. Therefore, 340° magnetic with a 15° westerly variation would be 325° true (i.e., 340° - 15° = 325°).

Unfortunately, the compasses on most boats and ships do not indicate magnetic directions. This is due to the use of ferrous materials in the boat's construction. As you know, ferrous metals affect compass needles. Large concentrations of ferrous metals, such as engine blocks, have particularly serious effects on compass readings. Compass errors due to the presence of ferrous metals aboard the boat are called deviations. Compasses are generally "swung" by compass adjustors to remove as much deviation as possible, but often small deviations remain. Since the metal masses change position relative to the compass magnets as the boat changes courses, deviation is recorded relative to the boat's heading. They are recorded in whole degrees and are labeled east or west, as are variations. Correcting from compass courses to magnetic courses, easterly deviations are added while westerly deviations are subtracted. Converting magnetic courses to compass courses, easterly deviations are subtracted, while westerly deviations are added. You ~~will~~ notice that this is consistent with the applications of variation.

There is an easy way to remember the appropriate direction of application of variation and deviation. If you consider true courses to be the most correct courses, and compass courses to be the least correct, simply remember "correcting add east". All other procedures are opposite. For example, uncorrecting add west; correcting subtract west; uncorrecting subtract east.

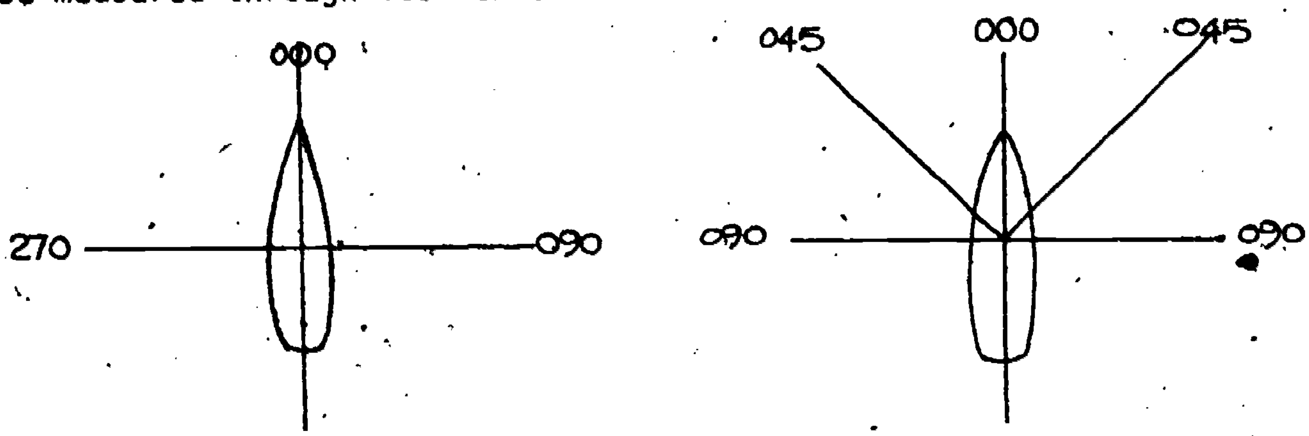
The difference between magnetic and true directions is probably worth student consideration since it does crop up in map reading, etc.

APPENDIX B
BEARINGS - SPECIAL TECHNIQUES



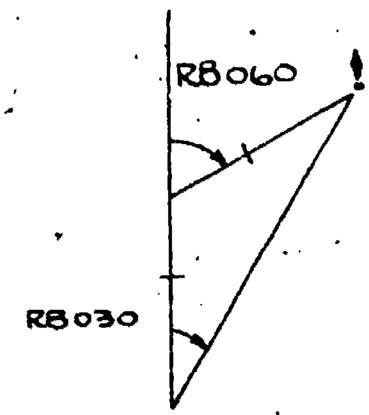
Hand-Bearing Compass

Several interesting techniques exist for the navigator which make interesting examples for geometry students. The first is called doubling the angle on the bow. It deals with relative bearings (RB) on an object of known position. A relative bearing is the angular measure from the centerline of the boat to the object. It is generally measured clockwise through 360°, but for this technique, it will just be measured through 180° on either side of the boat.

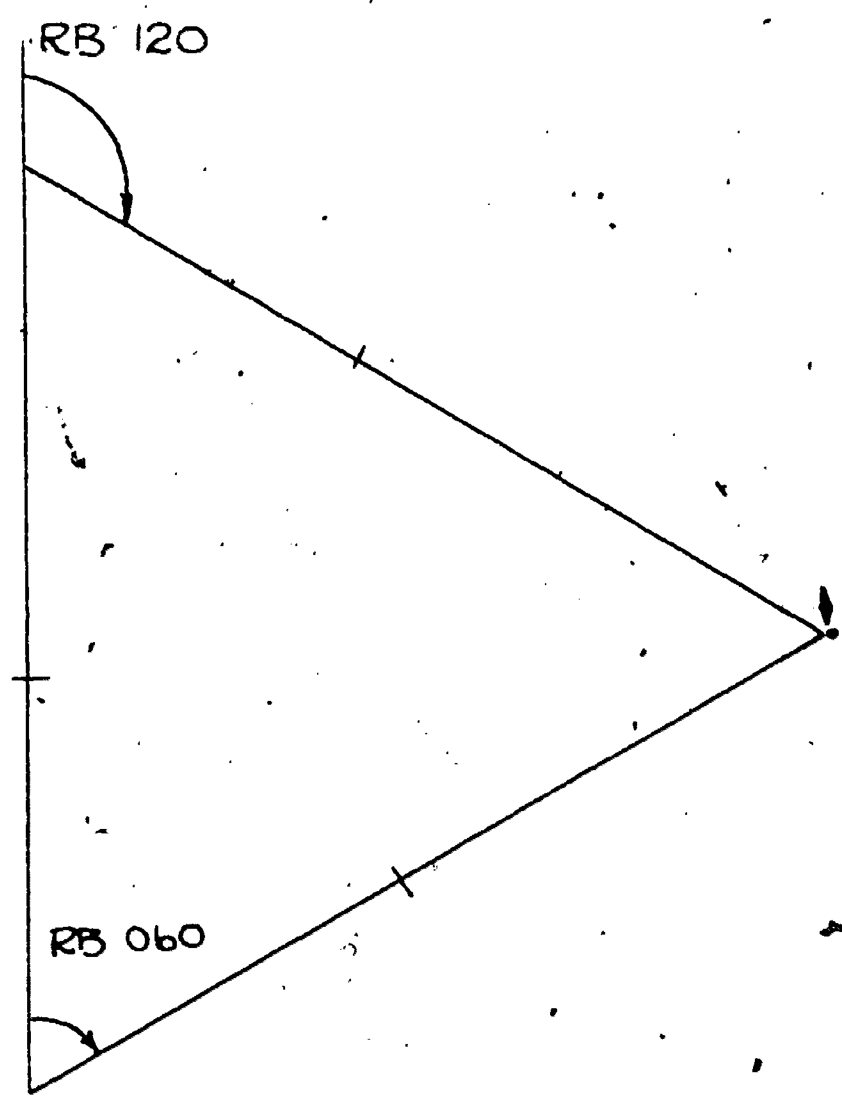


Normal 'RB' Doubling Angle 'RB'

In this technique, the relative bearing of an object such as a buoy is taken while the object is somewhere off the bow. Note the time, the course, and the speed of the boat at the time the bearing is taken. The relative bearing to the object is watched until it is twice its first bearing. At that instant, the time is noted and the compass bearing to the object is taken. At that time, the distance to the mark is the same as the distance you have traveled since the first bearing was taken. Your geometry students should be able to prove this using the appropriate theorems relative to supplementary angles and isosceles triangles.



Taking your first bearing when the object bears 60° relative, and your second when the object bears 120° relative is a special application of this practice. Your students should be able to recognize this as an equilateral triangle.



Problems

1. You are traveling at 6 knots in a straight line. At 1300, you find the relative bearing of a buoy to be 35°. At 1320, you find the relative bearing on the same buoy to be 70°. At 1320, how far were you from the buoy?

2. Geometry students. Prove that this technique works for any relative bearing for the first sighting and double that value for the second sighting.

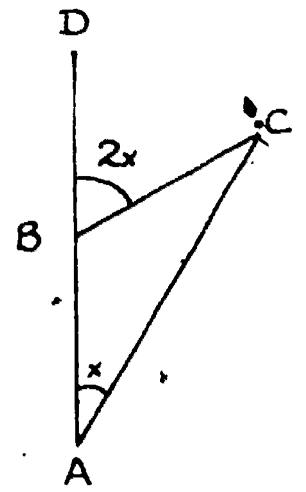
3. Using the fictitious Orono Bay chart, determine your position under the following circumstances: At 1410, you find the relative bearing of RB"HR" to be 30°. At 1440, you find the relative bearing of RB"HR" to be 60°, and its true bearing to be 045°. If you were traveling at 7 knots between 1410 and 1440, what is your approximate position at 1440? Give the coordinates of that position.

4. Geometry students. Prove that your distance from a buoy at first sighting and at second sighting will be the same, and that these will be the same as the distance you have traveled between sightings, if your first relative bearing is 60° and your second is 120°.

Answers

1. 2 nautical miles

2.

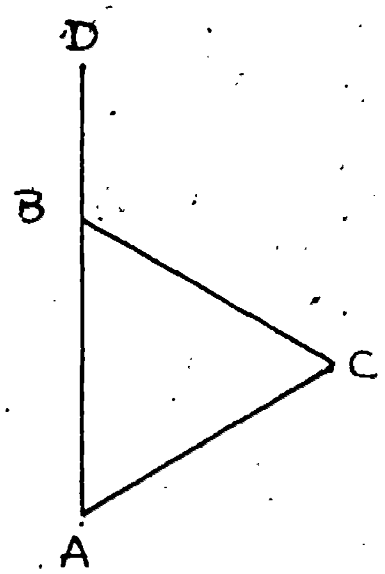


Given: $\angle A = X°$; $\angle DBC = 2X°$
Prove: AB = BC

1. $\angle A = X°$	1. Given
2. $\angle DBC = 2X°$	2. Given
3. $\angle ABC = 180 - 2X°$	3. Supplementary Angles
4. $\angle BCA = 180 - [(180-2X)+ X]$	4. Sum of the interior angles of a triangle is 180°
5. $\therefore \angle BCA = X°$	5.
6. $\therefore$ AB = BC	6. Sides opposite the base of an isosceles triangle are equal.

3. L 44° 01.8'N; lo 70° 14.4'W

4.



Given: $\angle A = 60°$
$\angle DBC = 120°$
Prove: AC = CB = BA

1. $\angle A = 60°$	1: Given
2. $\angle DBC = 120°$	2. Given
3. $\angle ABC = 60°$	3. Supplementary Angles
4. $\angle C = 60°$	4. Sum of the interior angles of a triangle is 180°
5. $\therefore$ AC = CB = BA	5. The sides of an equiangular triangle are all equal.

APPENDIX C
CURRENT SAILINGS

Introduction

A dead reckoning plot is always kept by navigators, but seldom does it actually represent the track a vessel covers over the bottom. As you know, dead reckoning accounts for three factors - speed of the boat through the water, length of time for which the boat moves through the water at that speed, and direction of that movement. One factor which nearly always causes a boat's path over the bottom to deviate from that projected by dead reckoning is current. Current is a movement of the water mass in which the boat is traveling. Considering some new variables now, provides an interesting opportunity for geometry, trigonometry, and physics students to further their inquiries into the chores of the navigator as they relate to school mathematics.

Currents generally result from persistent winds, from tidal flows, or from the Coriolis Effect resulting from the earth's rotation. The sources of the water's movement will have no real effect on our work here. If you have further interest in this, consult such reference works as Dutton's or Bowditch (see Bibliography).

Types of Current Problems

Three different types of current problems are commonly encountered by navigators. They include the following:

1. Situations in which boat speed through the water and heading are known, and set and drift of the current are known, and the actual track and speed of advance are to be found;

2. Situations in which boat speed, course and time are known and the boat's actual track and speed of advance are known; so, the set and drift of the current are to be found; and,

3. Situations in which set and drift of the current are known, intended track and desired speed of advance are known; so, the course to steer and speed to make through the water must be found.

Since solutions to current problems involve vector resolution and analysis, let's diagram these three situations for ease of understanding. But, let's define a few new terms first.

Actual Track, sometimes called course made good (CMG), is the movement a vessel has accomplished in reference to the ocean's bottom over a period of time.

Course (C) will be used synonymously with heading. That is, it is apparent direction in which the vessel is moving as determined by the compass.

Drift (D) is the speed of a current expressed in knots.

Estimated Position (EP) is assumed to be a slightly more accurate establishment of a vessel's position than a DR position in which another factor, such as current has been taken into account. An EP is less accurate than a fix. The EP is marked by a small square.

Intended Track is the desired movement of the vessel over the bottom, labeled ITR.

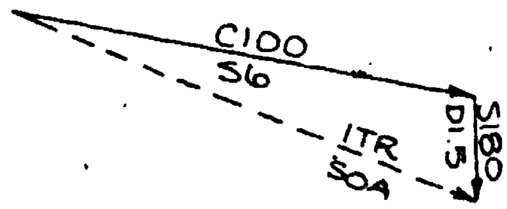
Set (S) of the current is the true direction toward which it flows.

Speed (S) will be used to identify the speed of the vessel through the water.

Speed of Advance (SOA) is the rate at which the vessel is covering the ground along its actual, or intended track. This is called speed made good (SMG), if it has been accomplished.

Current Sailing Situations

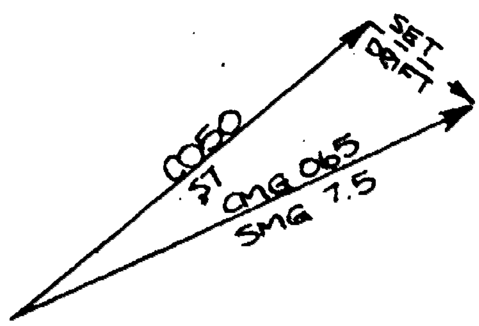
Situation 1.



Known: Boat speed and course, set and drift of the current.

Find: Intended track and speed of advance.

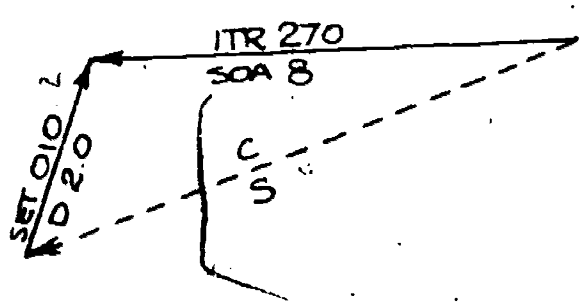
Situation 2.



Known: Boat speed and course, and course and speed made good.

Find: Set and drift of the current.

Situation 3.



Known: Intended track and speed of advance, and set and drift of the current.

Find: Course and speed.

Solution of Current Triangles

Students should solve these problems dealing with currents just as navigators do, that is graphically. This presents a good opportunity for teachers to teach their students about drawing to scale, and about "head to tail" resolution of vectors. Navigators would construct these problems right on their charts of the area they're sailing in, and students can do the same if you have NOAA charts, or have made rough charts of some fictitious area. (Sometimes, fixed based operators at local airports have to dispose of air charts as those in stock become obsolete about every three months. Contact your local general aviation terminal and see if you can have some of those charts.)

Let's use Situation 1. as an example for explanation. In that problem, boat speed is known to be 6 knots along a course line of 100° true. The current is known to be setting the boat toward the South (180°) at a rate of 1.5 knots. Have the students construct a course line 6 nautical miles long along the course 100° true. At the eastern end of that line, have them construct a line representing the current 1.5 nautical miles long heading due south. The "tail" of the current vector has now been constructed at the "head" of the course vector. By constructing a vector from the "tail" of the course vector to the "head of the current vector, the intended track and SOA can be represented. Intended track is represented by the direction of the vector and SOA is represented by its length in the same scale.

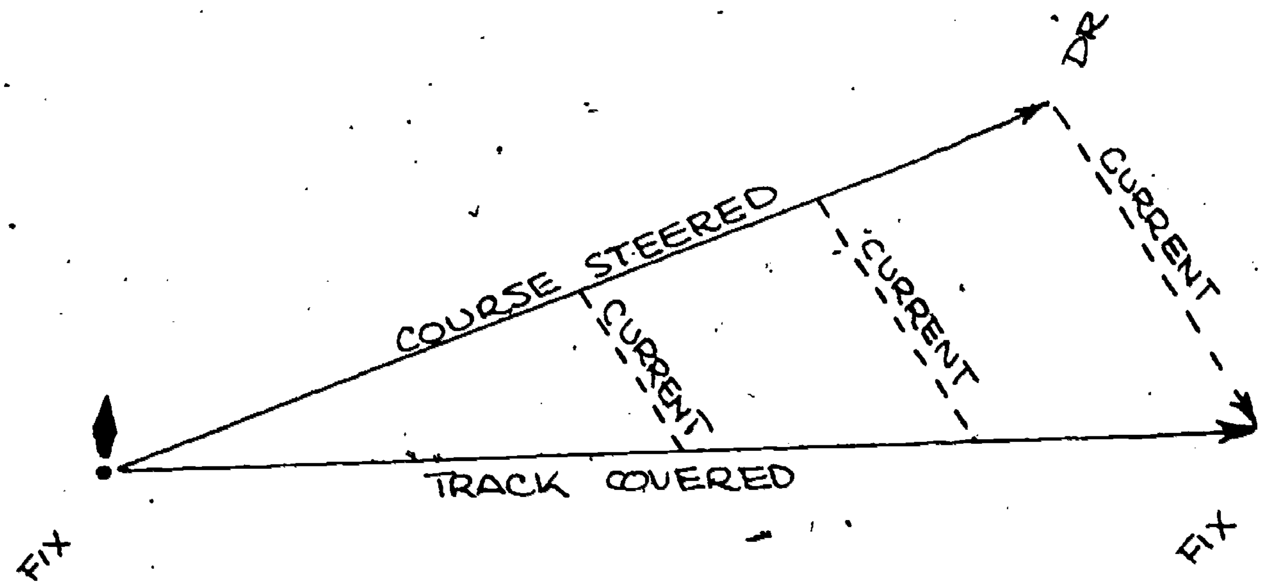
Proportionality can be discussed at this time, since any lengths of lines will result in an appropriate resolution as long as the two constructed lines are constructed proportionally.

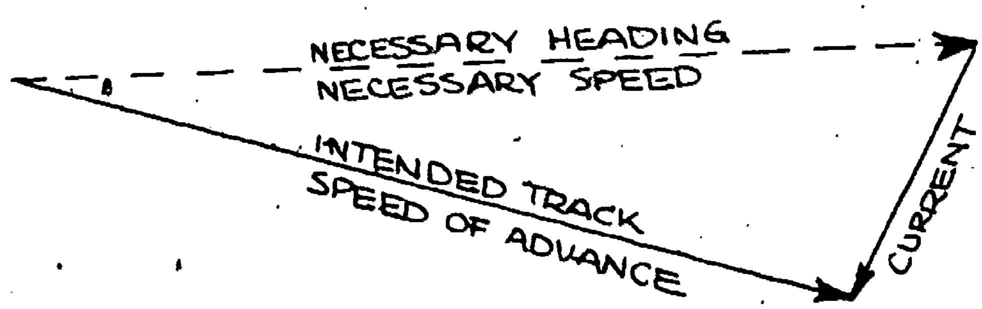
Situation 2. arises after a boat has steered a particular course at a known speed through the water for a known period of time from an accurate fix. At the end of that time, the navigator is able to fix the boat's position and finds that it is different from the position predicted by dead reckoning. He now knows what his track would have been in a no current situation, and he knows what his actual track was. The vectorial difference between these tracks is the current. It is solved by construction just as was the previous example. Plot the dead reckoning vector from the fix, then plot the actual track vector from the fix. The vector completing the triangle from the DR vector to the actual track vector represents the set and drift of the current. Measure this vector. If the length of time you've traveled since your last fix is just one hour, set up a proportion to determine the rate in knots. For example, if the current vector is 3.4 nautical miles long at the end of a course traveled for 1.7 hours, the following proportion would yield the current rate in knots.

$$\frac{3.4}{1.7} = \frac{x}{1} \text{ ; } x = 2 \text{ knots}$$

Geometry students can study the proportionality of the lengths of the sides of similar triangles by setting these problems up different periods of time of travel at the intersections of the courses and

Similar Triangle Proportionality




NECESSARY HEADING
NECESSARY SPEED
INTENDED TRACK
SPEED OF ADVANCE
CURRENT

currents and note the proportionality among the lengths of the sides. You might also note the possibility of discussing parallel lines and transversals.

Situation 3. is encountered when a navigator krows the track he wants to follow and the speed he wants to maintain, and the approximate set and drift of the current. He then must determine the heading he should steer and speed through the water that he should maintain to accomplish his intended track and speed of advance. He first plots his intended track and marks off the distance he would like to travel along that track in one hour. He then constructs the current vector head to head at the one hour mark on the intended track. This current vector gets its length from the distance the current would set you in one hour, and its direction from the direction in which the current is setting you. Now, by connecting the origin of the track vector with the "tail" of the current vector, the heading that must be maintained can be determined: The length of the course line yields the speed through the water which must be maintained to accomplish the intended speed of advance.

Many practical problems can be gleaned from these three types of situations. Follwing are examples for each type of situation.

Problems

1. If a helmsman steers 270° magnetic for one hour while his boat sails at 8 knots, what course will his actual track follow, and how long will it be at the end of that hour, if the current is setting 180 magnetic at 1 knot?

2. A ship head due north (000°) magnetic for two hours at 22 knots. At the end of that two hours, a fix shows that their actual track bore 010° manetic and was 46 miles long. What was the set and drift of the current? (Remember that the problem gives you a two hour time lapse.)

3. What course and speed must a boat maintain to actually cover 10 miles in the next hour and 15 minutes along a course of 135° magnetic, if the current is setting 315° magnetic at 175 knots?

Answers

1. Track 263°; distance made good 8 1/4 nautical miles.

2. Set 091°; drift 7.5 knots

3. Course 135° magnetic; speed 9 knots.

APPENDIX D
LATITUDE AT MERIDIAN PASSAGE OF THE SUN

Introduction

Determining approximate latitude using the sun's altitude at its zenith is a relatively easy task. It can be used to reinforce some of the mathematical concepts high school mathematics students have been acquiring, while introducing some new concepts about the relative positions of the Earth and the Sun. Further, it will demonstrate a practical application of some geometric concepts.

Concepts Stressed by the Process

Geometry students will see the use of the complement of an angle as the observed altitude of the sun (H_o) is converted to the polar distance (z). They will also note the use of the theorems which deal with parallel lines cut by a transveral if they determine the sun's altitude using the shadow of a stake in the ground.

Students studying trigonometry can see application of the tangent function in determining either H_o or z from the measurement of a stake's shadow at local apparent noon (LAN).

Algebra students will see the final solution of latitude determination to result from the solution of a linear equation, i.e. $L = z + dec.$ They will also have the opportunity to practice simple linear interpolations with whole numbers.

Physical Background

From our perspective, each day the sun rises somewhere in the eastern sky and traverses the sky in an arc to set somewhere in the western sky. The sun travels this arc at the rate of 15° per hour. Of course, we know that it is the Earth's west to east rotation that actually causes this apparent movement, but for the sake of our discussions here we'll act as though we're stationary and the sun is moving. Celestial navigators always adopt this perspective.

At the midpoint of its arc across the sky, the sun reaches its zenith just as it crosses our celestial meridian. This phenomenon happens at local apparent noon (LAN). LAN is at exactly the same zone time for every point at any given longitude on any day. But, since the sun is moving continually, the zone time of LAN is different for any two different longitudes.

If we can determine the angle between the horizon and the center of the sun at the instant the sun is at its zenith, it is a simple matter to compute our approximate latitude.

At two times of the year, the equinoxes, this would be particularly simple. That is because at those times when the sun is directly over the celestial equator, the latitude is equal to the complement of the observed altitude. Of course, the chances of the instant of the sun's passage from one celestial hemisphere to the other occurring just at our LAN is remote, indeed, but the precision of the instruments we will use for this exercise makes this concern totally unnecessary.

Since the sun is usually not right on the celestial equator, we must consider one more basic factor in our computations; this is declination. The apparent path of the sun among the stars is called the ecliptic. It is a great circle of the Earth. Due to the inclination of the Earth on its axis, this great circle is half in the Northern Hemisphere and half in the Southern Hemisphere crossing the equator at two points. This great circle forms an angle of approximately 23.5° with the equator. Hence, the sun is nearly always either north or south of the equator, up to 23.5°. This angular displacement of the sun north or south of the equator, declination, must be accounted for when determining latitude using the sun's altitude at LAN.

In actual navigational practice, declination at LAN is extracted from the Nautical Almanac to the tenth of a minute of arc. For our purposes in this activity, the included chart will provide the sun's declination to the nearest degree for each day of the year. Again, the precision of the makeshift instruments recommended for this unit make this level of accuracy in declination quite adequate.

We will apply no corrections to our determination of the sun's altitude in this activity, but you should realize that the navigator makes a number of corrections to his sextant observations to eliminate errors due to height of eye, refraction, semidiameter of the sun, and others.

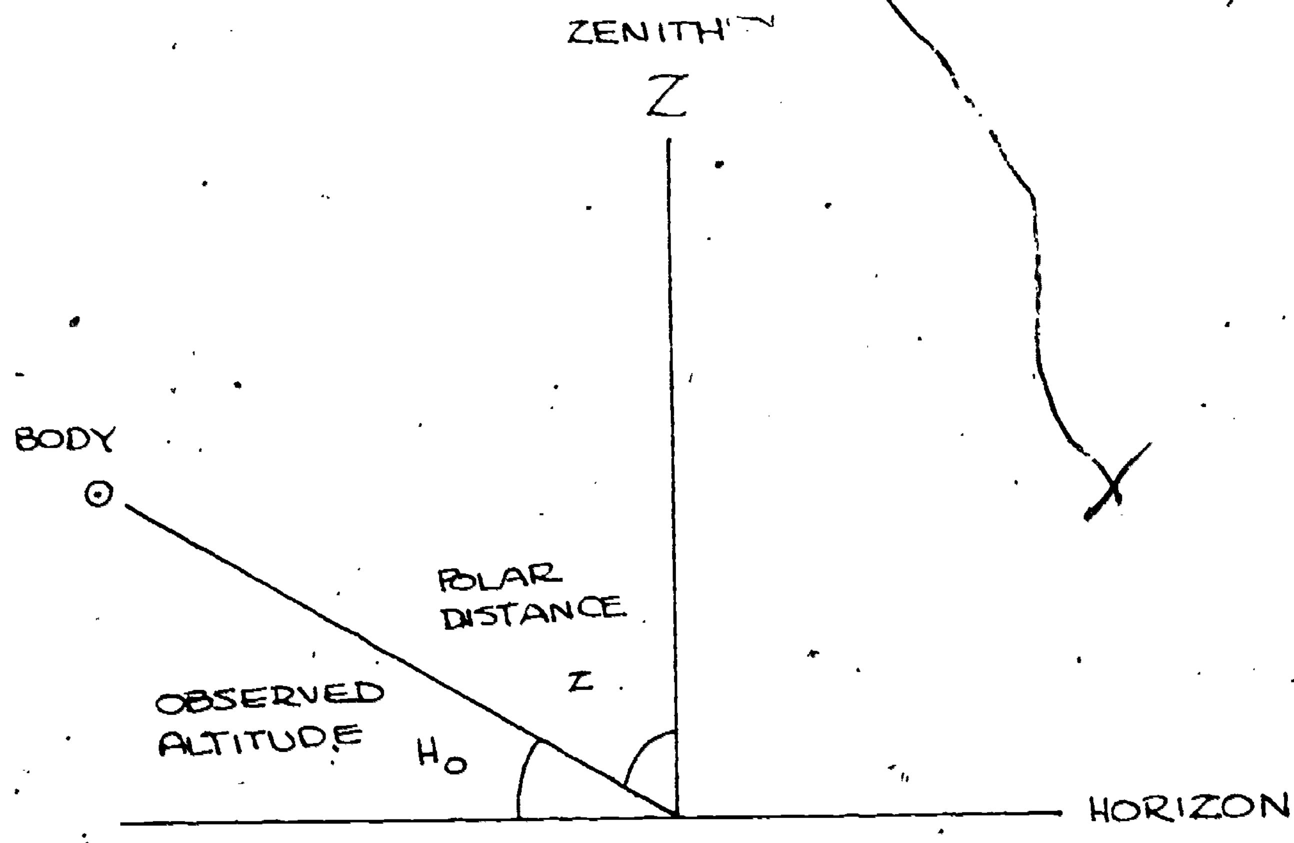
Determining Latitude - Finding Approximate LAN

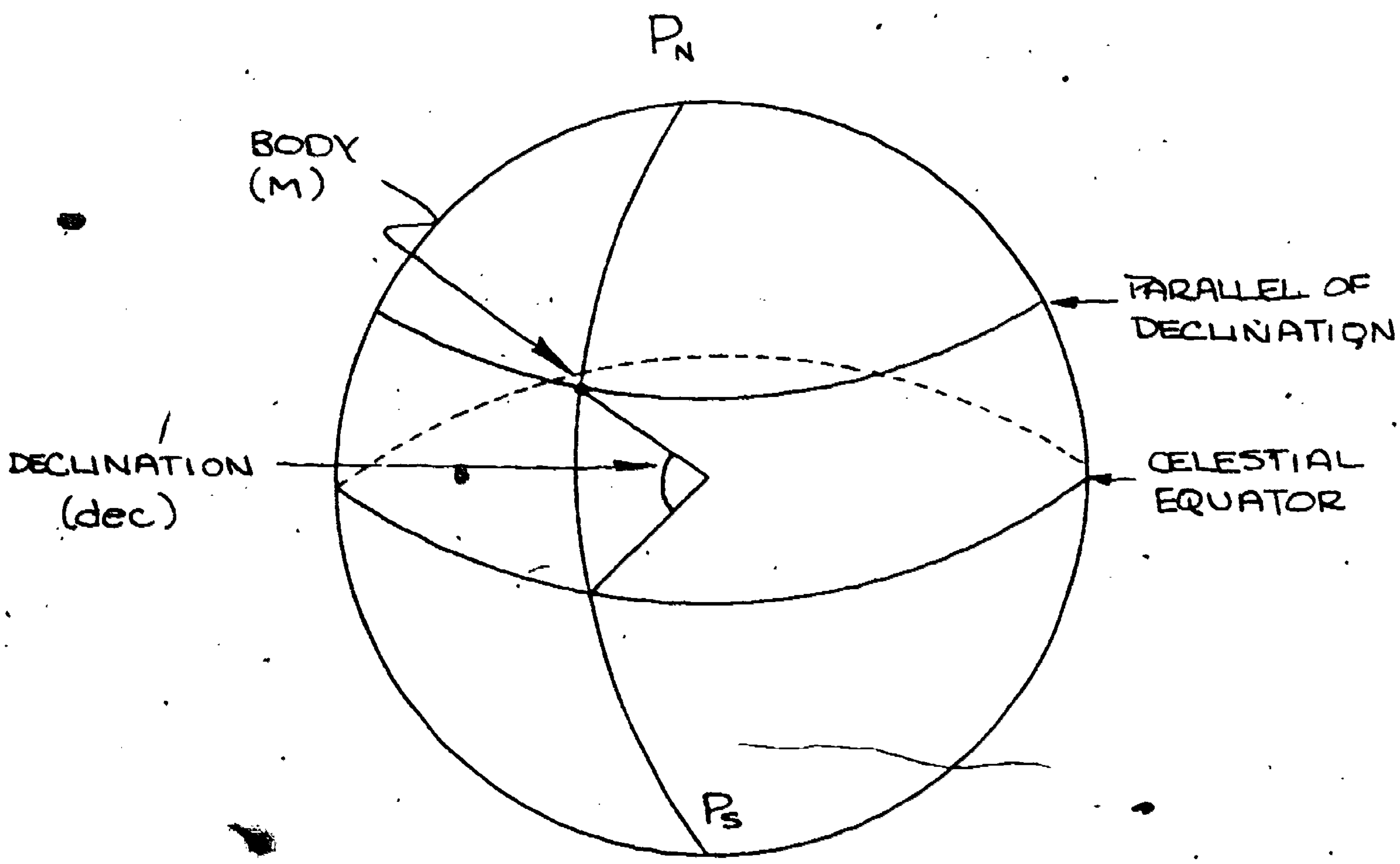
In order to know the approximate time at which the sun will cross our meridian, we must know our approximate longitude and the time of meridian passage of the sun on that particular day. Longitude can be found on a map or chart of your area. You can determine the time of meridian passage from the accompanying chart. This time is given for a number of days of the year; linear interpolation between these dates will produce satisfactory results.

To determine approximate LAN for your longitude, convert the difference in longitude between your longitude and the zone meridian to minutes of time using the following chart:

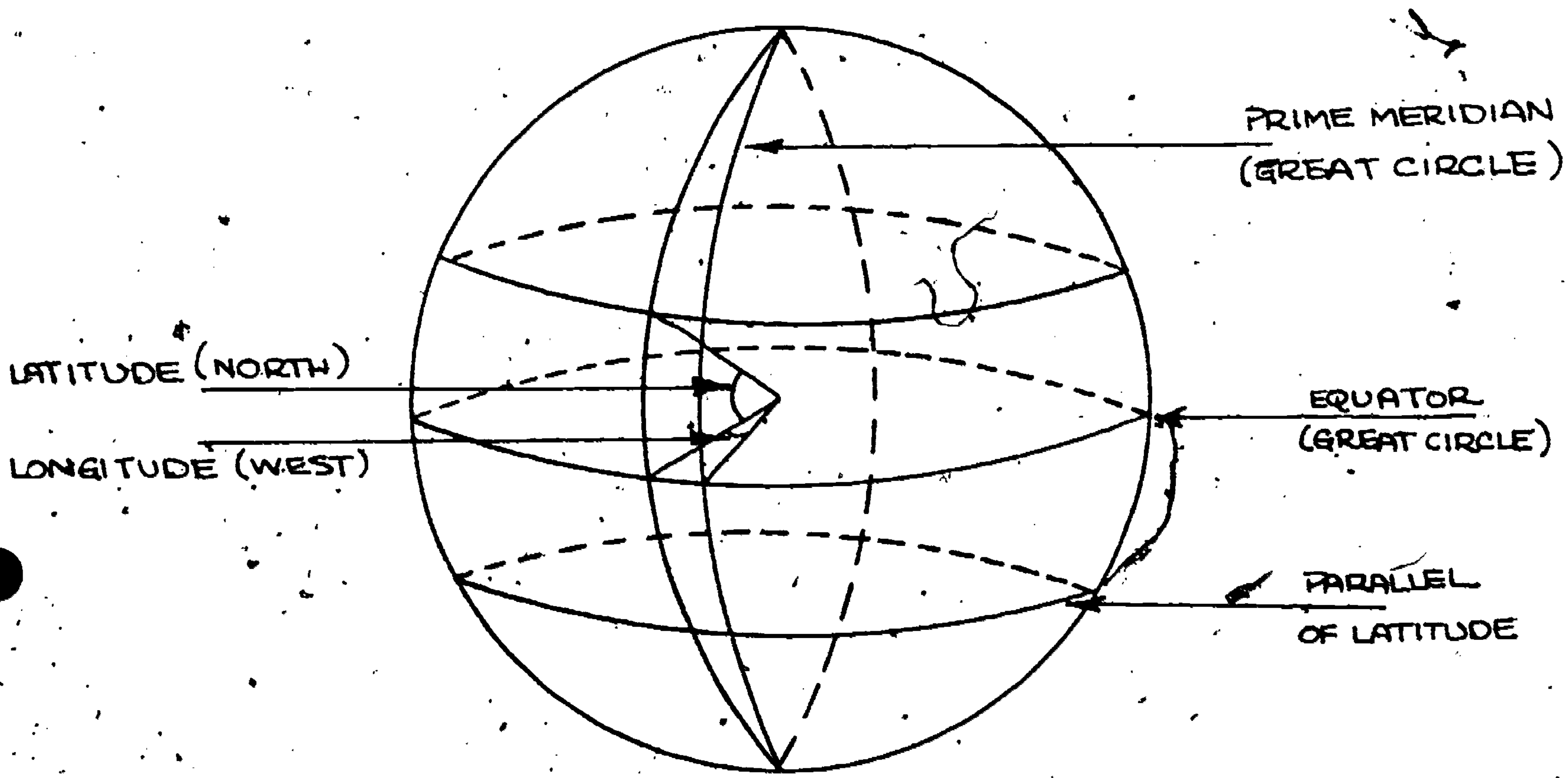
ARC	TIME
15°	1 hr.
1°	4 min.
15'	1 min.
1'	4 sec.

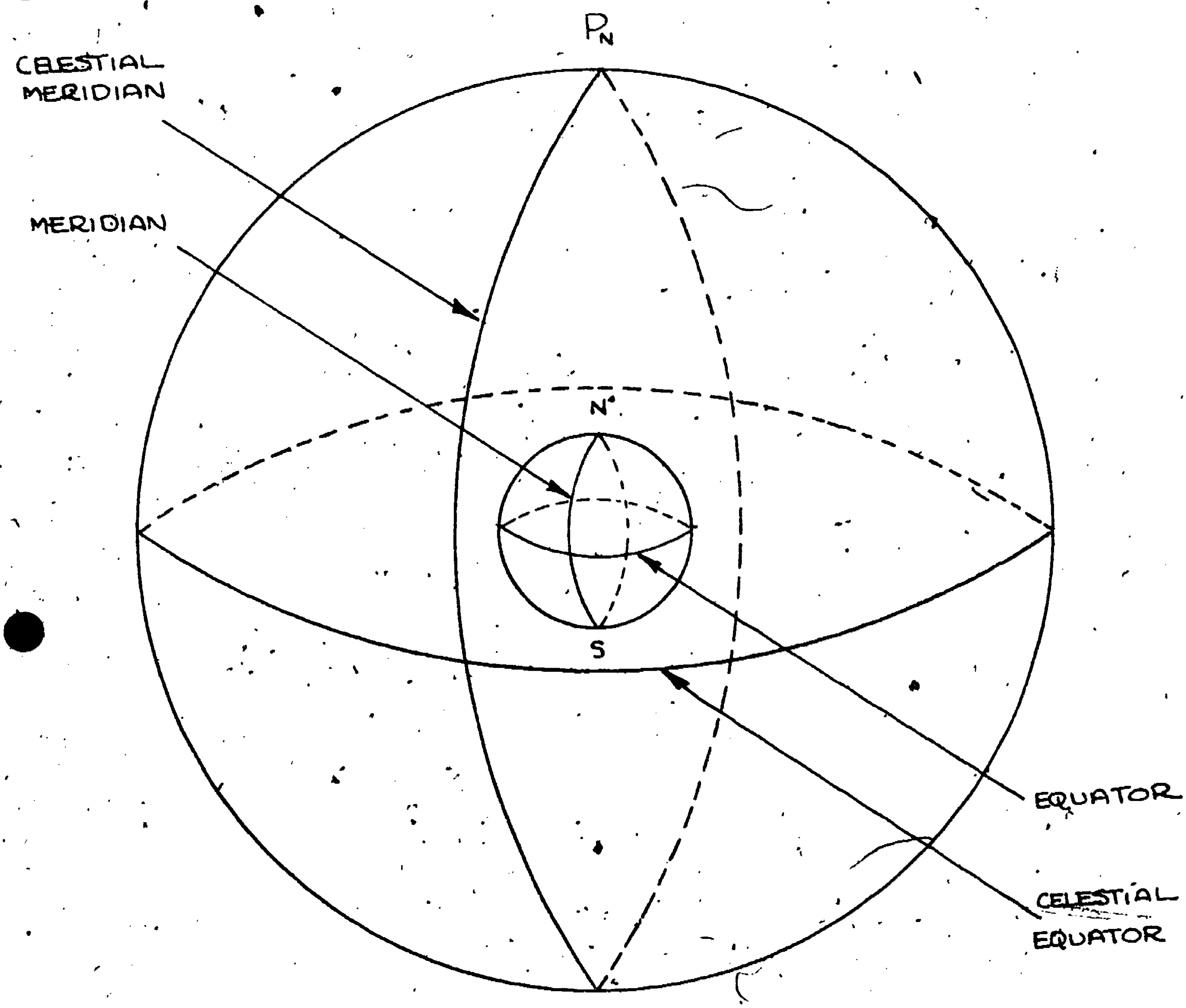
The zone meridian is the nearest meridian numbered with a multiple of 15°. For example, the zone meridian for the northeastern United States is 75°W.





The Measurement of Declination


PRIME MERIDIAN
(GREAT CIRCLE)
LATITUDE (NORTH)
LONGITUDE (WEST)
EQUATOR
(GREAT CIRCLE)
PARALLEL
OF LATITUDE



The Celestial Sphere

Once you have converted the difference in longitude between you and the zone meridian to time, apply the time to the appropriate time of meridian passage by adding the time difference if you are west of the zone meridian and subtracting it, if you are east of the zone meridian.

For example, if we are 5° 36' east of the zone meridian, and we have determined the time of meridian passage to be 1158, our computations would look like this.

5° 36' converted to time			
5°	=	20 min.	
30'	=	2 min.	
6'	=		24 sec.
5° 36'	=	22 min.	24 sec.

Since we're east of the meridian,

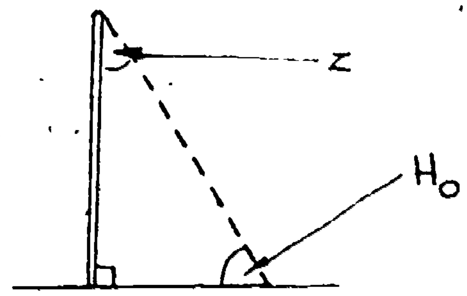
11	58	00	(time of meridian passage)
–	22	24	(longitude difference converted to time)
11	35	36	

So, 11 35 36 would be the approximate time at which the sun would reach its zenith and cross our meridian on that day. If one doesn't have access to this information, such as while adrift in a lifeboat, the sun can simply be watched. Taking continuous altitude readings, one could identify LAN by simply noting the highest altitude attained by the sun. Add one hour to your computations if you are using Daylight Savings Time instead of Zone Time.

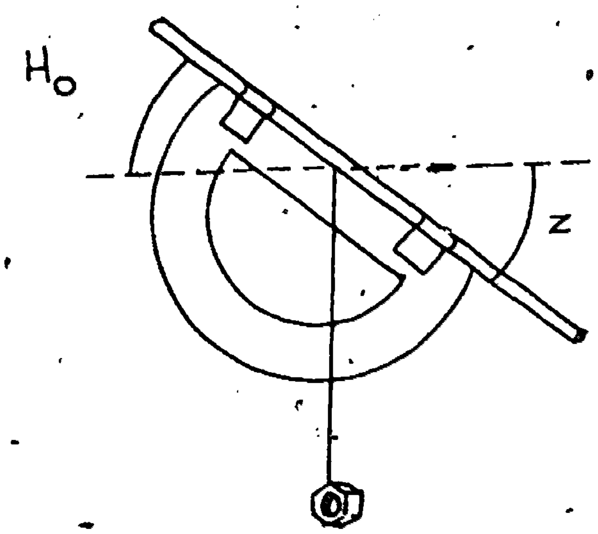
Determining the Sun's Altitude

While the navigator uses a sextant to accurately determine the sun's apparent altitude, we will use rougher methods to avoid adding further confusing new concepts.

A very simple method of determining the sun's altitude involves driving a stake vertically into the ground. Drive it into the flat ground as nearly perpendicular to the ground as you can. A plumb bob will help. Measure the shadow cast by the stake as LAN approaches and passes. Keep track of the shortest measurement you obtain. If your students are familiar with trig functions, have them determine the angle formed between the end of the shadow and the hypotenuse of the triangle using the tangent function. If they are not, you can compute that angle for them. This angle is your observed altitude, H_0. The complement of this angle, which is also the angle between the stake and the hypotenuse of the triangle, is called the polar distance, or z.



Another simple method of determining the sun's altitude at LAN is to tape a common drinking straw along the base of a large plastic protractor. From the center reference mark on the protractor, suspend a weight from a fine thread. Do not allow students to sight the sun through the straw! Have the students focus the straw directly at the sun by observing the shadow cast on a plain sheet of paper. The shadow of the straw will be just a sharp circle when the straw is pointed directly at the sun. At that time, the altitude can be read where the thread crosses the arc of the protractor.



Note that the angle between the base of the protractor and the thread is z, or the complement of H_o.

Determining Latitude

Once you have determined H_o, or z, and declination, you are ready to calculate latitude. Our explanation will deal with situations only involving the Northern Hemisphere and latitudes north of 23.5°N. Under those circumstances, the sun is always south of the observer's zenith at LAN.

When the sun is in the northern declinations, the following formula can be used to determine latitude:

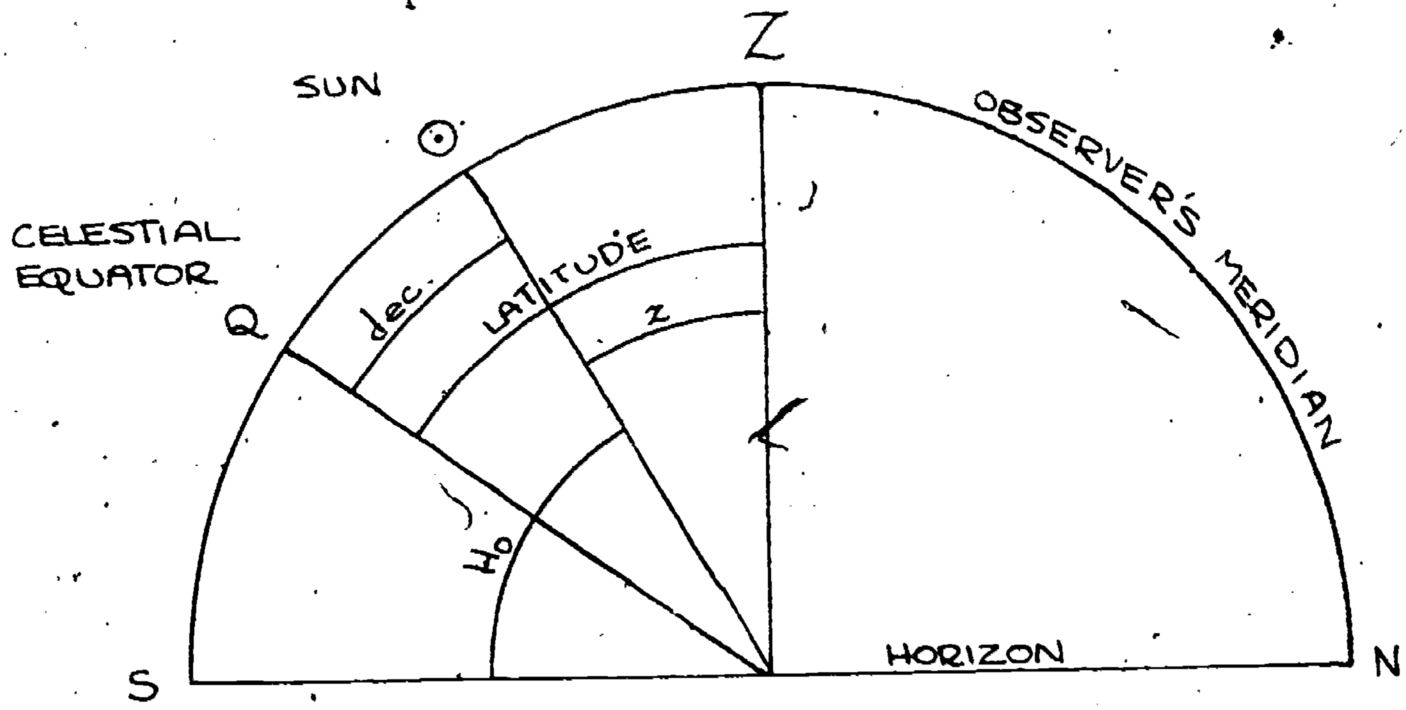
$$\text{latitude (L)} = z + \text{dec.}$$

Remember that z is the complement of H_o.

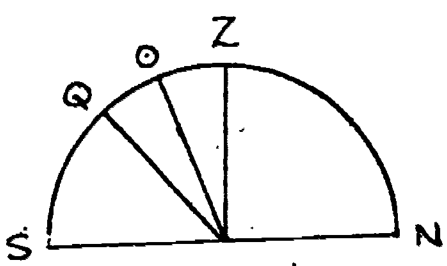
When the sun is in the southern declinations, the following formula applies:

$$\text{latitude} = z - \text{dec.}$$

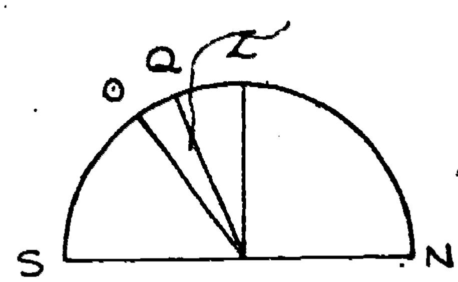
OBSERVER'S ZENITH



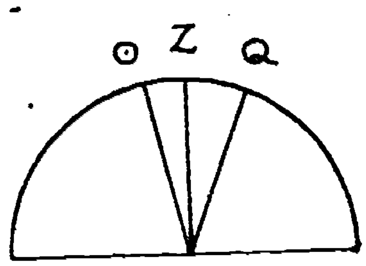
dec = DECLINATION
z = POLAR DISTANCE
H_o = OBSERVED ALTITUDE
L = LATITUDE



$L = z + dec$



$L = z - dec$



$L = dec - z$

Declinations of the Sun to the Nearest Degree

Jan.	1	S23		25	S9		20	N11		13	N23
	2	23		26	9		21	12		14	23
	3	23		27	8		22	12		15	23
	4	23		28	8		23	13		16	23
	5	23					24	13		17	23
	6	23	Mar.	1	8		25	13		18	23
	7	22		2	7		26	13		19	23
	8	22		3	7		27	14		20	23
	9	22		4	6		28	14		21	23
	10	22		5	6		29	14		22	23
	11	22		6	6		30	15		23	23
	12	22		7	5					24	23
	13	21		8	5	May	1	15		25	23
	14	21		9	5		2	15		26	23
	15	21		10	4		3	16		27	23
	16	21		11	4		4	16		28	23
	17	21		12	3		5	16		29	23
	18	21		13	3		6	17		30	23
	19	20		14	3		7	17			
	20	20		15	2		8	17	July	1	23
	21	20		16	2		9	17		2	23
	22	20		17	1		10	18		3	23
	23	19		18	1		11	18		4	23
	24	19		19	1		12	18		5	23
	25	19		20	0		13	18		6	23
	26	19		21	0		14	19		7	23
	27	18		22	N1		15	19		8	22
	28	18		23	1		16	19		9	22
	29	18		24	1		17	19		10	22
	30	18		25	2		18	20		11	22
	31	17		26	2		19	20		12	22
				27	3		20	20		13	22
Feb.	1	17		28	3		21	20		14	22
	2	17		29	3		22	20		15	22
	3	17		30	4		23	21		16	21
	4	16		31	4		24	21		17	21
	5	16					25	21		18	21
	6	16	Apr.	1	5		26	21		19	21
	7	15		2	5		27	21		20	21
	8	15		3	5		28	21		21	20
	9	15		4	6		29	22		22	20
	10	14		5	6		30	22		23	20
	11	14		6	6		31	22		24	20
	12	14		7	7					25	20
	13	13		8	7	June	1	22		26	19
	14	13		9	8		2	22		27	19
	15	13		10	8		3	22		28	19
	16	12		11	8		4	22		29	19
	17	12		12	9		5	23		30	19
	18	12		13	9		6	23		31	18
	19	11		14	9		7	23			
	20	11		15	10		8	23	Aug.	1	18
	21	11		16	10		9	23		2	18
	22	10		17	10		10	23		3	18
	23	10		18	11		11	23		4	17
	24	S10		19	N11		12	N23		5	N17

The prefix N denotes a northern declination; the prefix S denotes a southern declination.

Aug.	6	N17		27	S2		17	S19
	7	16		28	2		18	19
	8	16		29	2		19	19
	9	16		30	3		20	20
	10	16					21	20
	11	15	Oct.	1	3		22	20
	12	15		2	4		23	20
	13	15		3	4		24	21
	14	14		4	4		25	21
	15	14		5	5		26	21
	16	14		6	5		27	21
	17	13		7	5		28	21
	18	13		8	6		29	21
	19	13		9	6		30	22
	20	12		10	7			
	21	12		11	7	Dec.	1	22
	22	12		12	7		2	22
	23	11		13	8		3	22
	24	11		14	8		4	22
	25	11		15	8		5	22
	26	10		16	9		6	22
	27	10		17	9		7	23
	28	10		18	10		8	23
	29	9		19	10		9	23
	30	9		20	10		10	23
	31	9		21	11		11	23
				22	11		12	23
Sept.	1	8		23	11		13	23
	2	8		24	12		14	23
	3	8		25	12		15	23
	4	7		26	12		16	23
	5	7		27	13		17	23
	6	6		28	13		18	23
	7	6		29	13		19	23
	8	6		30	14		20	23
	9	5		31	14		21	23
	10	5					22	23
	11	5	Nov.	1	14		23	23
	12	4		2	15		24	23
	13	4		3	15		25	23
	14	3		4	15		26	23
	15	3		5	16		27	23
	16	3		6	16		28	23
	17	2		7	16		29	23
	18	2		8	17		30	23
	19	2		9	17		31	S23
	20	1		10	17			
	21	1		11	17			
	22	0		12	18			
	23	0		13	18			
	24	0		14	18			
	25	S1		15	18			
	26	S1		16	S19			

The prefix N denotes a northern declination; the prefix S denotes a southern declination.

Times of Meridian Passage of the Sun

Jan. 1	1204
Feb. 22	1214
April 15	1200
May 21	1156
June 14	1200
July 12	1206
Aug. 8	1206
Sept. 1	1200
Oct. 23	1144
Nov. 14	1144
Dec. 25	1200

1978 Nautical Almanac

GLOSSARY

Altitude	The angular distance from the horizon to the body
Celestial Equator	An imaginary line dividing the celestial sphere into northern and southern hemispheres. This equator is directly above the terrestrial equator.
Celestial Meridian	An imaginary line running from the North Celestial Pole to the South Celestial Pole. The celestial meridians coincide with terrestrial meridians.
Declination	The angular distance of a body north or south of the celestial equator. A measurement similar to the measurement of latitude on the earth's surface.
Ecliptic	The apparent path of the sun through the heavens. This path is a great circle path.
Equinox	Literally "equal nights". When the sun's path crosses the celestial equator, the day and night are each approximately 12 hours in length.
Great Circle	Any circle on the surface of a sphere which has the center of the sphere as its center. The radius of the great circle is, therefore, the radius of the sphere.
LAN	See Local Apparent Noon
Latitude	(L) the angular distance of a point on the earth's surface north or south of the terrestrial equator. Parallels of latitude are imaginary lines running around the earth east and west. The equator is a parallel of latitude and is a great circle; the other parallels of latitude are small circles.
Local Apparent Noon	(LAN) the time of day when the apparent sun crosses the local meridian.
Longitude	(Lo) the angular distance of a point on the earth's surface east or west of the prime meridian. The prime meridian runs through Greenwich, England. All meridians of longitude are gret circles.
Meridian	An imaginary line on the earth's surface running from pole to pole. The combination of the upper and lower branches of any meridian form a great circle.

Meridian Passage	The movement of a celestial body across the upper branch of an observer's meridian. Altitudes of many bodies taken at the instant of meridian passage can be used to determine latitude.
Observed Altitude	(Ho) in navigational practice, observed altitude is the measured altitude of the body with applied corrections.
Polar Distance	(z) the complement of observed altitude (Ho), (that is, the angular distance from the body to the elevated celestial pole.)
Zenith	The point on the celestial sphere directly over the observer's head.
Zone Meridian	The meridian at the center of each time zone. The meridians begin at the prime meridian and extend east and west at 15° intervals. The zone meridian for the eastern U.S. is the meridian through 75°W longitude.
Zone Time	Is time based on the zone meridians. Longitudes west of the prime meridian are + time zones, and have times earlier than Greenwich, while longitudes east of the prime meridian are - time zones and are later than Greenwich. The numbering of the time zones is based upon the number of 15° increments the zone meridian is east or west of the prime meridian. For example, the eastern U.S. uses the meridian through 75° W longitude as its zone meridian. That makes the zone description +5; therefore, to determine Greenwich Mean Time, simply add five hours to our zone time.

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