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ELEMENTARY TREATISE

ON

NAVIGATION

AND

NAUTICAL ASTRONOMY

BY

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## PREFACE

THE following pages are the outcome of the author's own teaching. To understand the principles set forth in them a knowledge of elementary Plane and Spherical Geometry and Trigonometry is all that is needed.

The author wishes to acknowledge special obligations to Martin's "Navigation" and Bowditch's "Navigator." To either of these works the present book might serve as an introduction.

Most of the examples have been worked by means of Bowditch's "Useful Tables," published by the United States Government. The corrections to Middle Latitude have been taken from the table (pages 172, 173) prepared by the author.

References to *Elements of Plane and Spherical Trigonometry* by the author and to *Elements of Geometry* by Phillips and Fisher are indicated by (Trig.) and (P. and F.) respectively.





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# NAVIGATION AND NAUTICAL ASTRONOMY

## CHAPTER I

### PLANE SAILING — MIDDLE LATITUDE SAILING — MERCATOR'S SAILING

IN navigation the *earth* is regarded as a *sphere*. Small parts of its surface (as in surveying) are considered as *planes*.

Art. 1. The *axis* of the earth is the *diameter* about which it revolves. The extremities of this axis are called *poles*, one being named the North Pole and the other the South Pole.

2. The *meridian* of any point, or place, on the earth is the *great circle* arc passing through the point, or place, and through the poles of the earth.

The meridian of a point, or place, may be said to be the intersection of a plane with the surface of the earth, the plane being determined by the axis and the point (Phillips and Fisher, *Elements of Geometry*, 526, 807).

(a) Meridians are, therefore, *north* and *south* lines.

3. The earth's *equator* is the circumference of the great circle, whose plane is *perpendicular* to the axis.

(a) The equator is perpendicular, therefore, to the meridians (P. and F., 837).

4. *Parallels* of latitude on the earth are circumferences of *small* circles, whose planes are *perpendicular* to the *axis*.

The planes of these parallels are parallel to each other and to the plane of the equator (P. and F., 559).

(a) *Parallels of latitude* are *east* and *west* lines.

5. The *longitude* of a point, or place, is the *angle* between the plane of the meridian of the point, or place, and the plane of some fixed meridian. This angle is measured by the arc of the equator intercepted between these planes, since this arc measures the plane angle of the dihedral angle of the planes (P. and F., 836). This *arc*, intercepted between the two meridians, is spoken of as *the longitude*, as its degree measure is the same as that of the dihedral angle.

One assumed meridian from which longitude is reckoned is the meridian of the Observatory of Greenwich, England; another is the meridian of the Observatory of Washington. The French, also, have a fixed meridian from which longitude is reckoned.

(a) Longitude is reckoned, on the *arc* of the equator, east and west of the assumed meridian, from  $0^\circ$  to  $180^\circ$ .

(b) The *difference of longitude* of two places is the angle between the planes of their meridians, and is measured by the arc of the equator intercepted between these meridians.

This arc is evidently the difference of the two arcs, which measure the longitudes of the two places,

if the places are either both E. or both W. of the assumed meridian.

(c) If we give to E. longitudes the sign +, and to W. longitudes the sign -, the arc which measures the difference of longitude of two places will always be the *algebraic* difference of the longitudes of the places.

(d) To find, then, the *difference* of longitude of two places whose longitude is given, we *subtract* the *less* from the greater if both are E. or both are W., but add the two if one is E. and the other W.

6. The *latitude* of a point, or place, is the *angle* made with the plane of the equator by a line drawn from this point, or place, to the center of the earth. The latitude is measured by the arc of the meridian (of the point) which subtends the angle. This subtending *arc* is spoken of as *the latitude*, as its degree measure is the same as that of the inclination of the line to the plane of the equator.

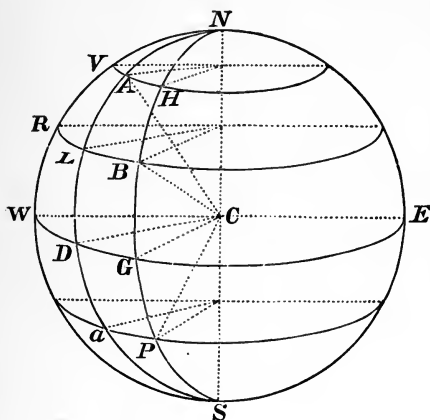
Latitude is reckoned from  $0^\circ$  to  $90^\circ$ , north and south of the equator.

7. The *difference of latitude* of two places is the difference between the latitudes of the two places, difference being understood as *algebraic*, and north latitudes having the sign + and south latitudes the sign -.

(a) To find, then, the *difference of latitude* of two places whose latitudes <sup>are</sup> given, take the less from the greater if both are N. or both are S., but add the two if one is N. and the other S.

(b) The *difference of latitude* of two places is measured on *any arc of a meridian intercepted between the parallels of latitude of the places.*

Let the figure represent a hemisphere of the earth. Let  $N$  and  $S$  be the poles;  $C$  the center; and  $WDE$  the equator. Suppose  $A$  and  $B$  to be two points on the surface;  $VAH$  to be the parallel of latitude of  $A$ , and  $NAS$  to be its meridian;



$RLB$  to be the parallel of latitude, and  $NBS$  the meridian of  $B$ . Then it is to be proved that the difference of latitude of  $A$  and  $B$  is measured by  $AL$ ,  $HB$ ,  $VR$ , or any other meridian arc intercepted between  $VAH$  and  $RLB$ .

Let the meridian  $NAS$  intersect the parallel  $RLB$  in the point  $L$ , and the equator in the point  $D$ . Also, let the meridian  $NBS$  intersect the parallel  $VAH$  in the point  $H$ , and the equator in the point  $G$ . Draw the straight lines  $CA$ ,  $CD$ ,  $CB$ , and  $CG$ .

The plane of the meridian  $NAS$  is perpendicular to the plane of the equator (Arts. 2 and 3), and is, therefore, the plane which projects the line  $CA$  upon that plane;  $CD$  is the intersection of these two planes (P. and F., 528), and contains (as a part of it) the projection of the line  $CA$ . The angle  $ACD$  is, therefore, the angle made by the line  $AC$  with the plane of the equator (P. and F., 586), and is, consequently, the latitude of the point  $A$  (Art. 6). Also, the plane of the meridian,  $NGS$ , is perpendicular to the plane of the equator,

and by its intersection with that plane determines the projection of the line  $CB$  upon the plane. Therefore,  $BCG$  is the latitude of the point  $B$ .

Now,  $ACD$ , or the latitude of  $A$ , is measured by  $AD$ , and  $BCG$  is measured by  $BG$ ; therefore, the difference of latitude of  $A$  and  $B$  is measured by the difference between  $AD$  and  $BG$ ; that is, by  $AD - BG$ .

$$AD = ND - NA = NG - NH = NW - NV \text{ (P. and F., 817).}$$

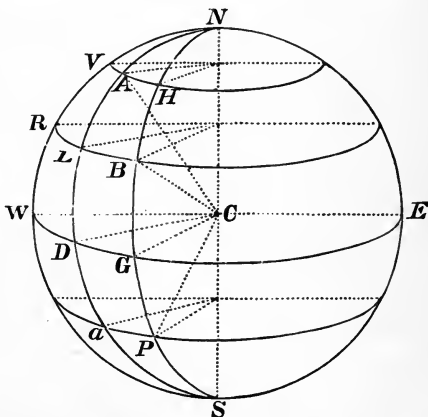
$$\text{Also, } BG = ND - NL = NG - NB = NW - NR.$$

$$\begin{aligned} \therefore AD - BG &= NL - NA = NB - NH = NR - NV; \\ &= AL = HB = VR, \text{ etc.} \end{aligned}$$

If the point  $P$  be taken on a parallel of latitude south of the equator, the difference of latitude would be measured by  $HP$  or by  $Aa$ , an arc of a meridian intercepted between the parallels.

8. It is evident that *the position of any point or place on the earth's surface is determined if the latitude and longitude of the point, or place, are known.*

Thus, suppose  $NWSE$  to represent a hemisphere of the earth;  $NWS$  to be the meridian from which longitude is reckoned;  $WDE$  to be the arc of the equator;  $RLB$  and  $VAH$  to be parallels of latitude; and  $NDS$ ,  $NBS$  to be meridians.



Suppose the latitude of the point to be  $30^\circ$  N., and the longitude to be  $40^\circ$  E. If, now,  $RLB$  be a parallel of latitude, of which the polar distance  $NR$ ,  $NL$ ,

or  $NB$  is  $60^\circ$ , since  $NW$ ,  $ND$ , or  $NG$  is  $90^\circ$ ,  $WR$ ,  $DL$ , or  $GB$  is  $30^\circ$ ; therefore,  $RLB$  is a parallel of *latitude*, every point of which is  $30^\circ$  N. of the equator. Consequently, the point whose latitude is given must be found somewhere on this arc  $RLB$ . Again, if  $NDS$  be a meridian, whose plane  $NDS$  makes with the plane  $WNS$  an angle of  $40^\circ$  (measured by the arc  $WD$  of the equator), the *longitude* of every point on  $NDS$  is  $40^\circ$  E. Therefore, the point whose longitude is given must be somewhere on the meridian  $NDS$ . Since the point is on the arc  $RLB$ , and at the same time on the arc  $NDS$ , it must be at their intersection,  $L$ . Therefore, the point is *determined* when its latitude and longitude are given.

It might be said that two circles intersect twice, and therefore that the point of the circle  $RLB$  diametrically opposite to  $L$  would be indicated by lat.  $30^\circ$  N., long.  $40^\circ$  E. This is evidently false, since the other half of  $NDS$  and the other half of  $RLB$ , which, by their intersection, determine this second point, are on the other hemisphere. The *latitude* of this second point is  $30^\circ$  N., but its *longitude* is  $140^\circ$  W. of the assumed meridian (Art. 5, (a)).

9. As charts of the earth's surface are constructed for the use of navigators with meridians and parallels of latitude either drawn on them, or indicated, if a ship's *latitude* and *longitude* are known, the position of the ship is determined. It is important that this position should be determined from day to day, and therefore it is important that the ship's latitude and longitude should be known. Latitude and longitude are best obtained by observations of the heavenly bodies. This is a department of navigation which belongs to astronomy. It is necessary to have other methods of determining a ship's position when it is impossible to resort to the methods of astronomy. These other methods are now to be considered.

10. (a) The *distance* sailed by a ship, in going from one point to another, is the *length* of the line traversed by the ship between the two points.



(b) The *bearing* or *course* of a ship, at any point, is the *angle* which the line traversed by the ship (that is, the *distance*) makes with the meridian passing through that point.

If a ship cuts every meridian at the *same angle*, she is said to continue on the *same course*.

If a ship is said to sail a given distance on a given course, it is assumed that in that distance she continues on the *same course*.

The path made by a ship continuing on the same course is called a *rhumb line*, or simply a *rhumb*.

(c) The *departure* of a ship, in sailing from one point to another, is the whole east or west distance she makes measured from the meridian from which she sails, and is an easting or westing according as she sails in an easterly or westerly direction.

If the distance sailed is *small*, it may be considered a straight line, and the departure might also be regarded as a *straight* line measuring the perpendicular distance between the meridians of the two points. In this case the *meridians* may be considered parallel straight lines (as in surveying), since they are lines on a small portion of the earth's surface, and are perpendicular to the same line.

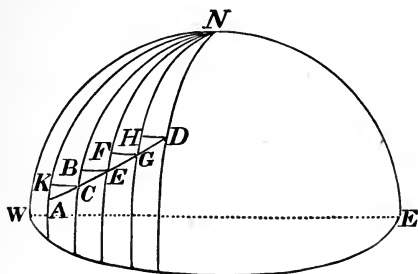
If the distance is *not* small, it may be divided up into such a number of small parts that each of them may be considered as a straight line. The departure of each of these small distances will then also be a *straight* line, and the departure of the *whole* distance will be the sum of the departures of the parts.

(d) *Difference of latitude* of two points has already been defined (Art. 7).

If a given distance sailed by a ship is small, it may be regarded as a straight line, and then the difference of latitude of the two extremities of the line, representing this distance, is measured by a line, which may be also regarded as a straight line. The difference of latitude is then a northing or southing (as in surveying).

If the distance is *not* small, it may be divided into such a number of parts that each part may be small enough to be considered a straight line. The difference of latitude of each part will then be a straight line, and the difference of latitude of the whole distance will be the sum of the differences of latitude of the parts.

Thus, suppose  $AC$  to be a small distance on the earth's surface. Let  $AK$  and  $BC$  be meridians of the points  $A$  and  $C$ , and



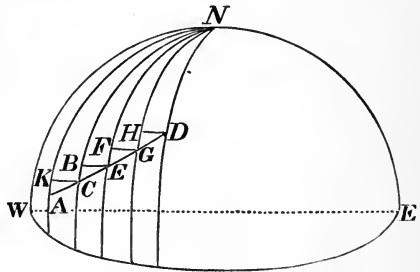
let these lines be considered parallel. If  $CK$  be a perpendicular to  $AK$  drawn from  $C$ , it will be the departure of  $AC$ , and  $AK$  will be the difference of latitude of  $A$  and  $C$ , or the difference of latitude for the distance  $AC$ .

If the distance be a *long* distance, as from  $A$  to  $D$ , then it can be divided into such a number of short distances — as, for instance,  $AC$ ,  $CE$ ,  $EG$ , and  $GD$  — that each one of them can be considered as a straight line. If  $AK$ ,  $CB$ ,  $EF$ , and  $GH$  be the

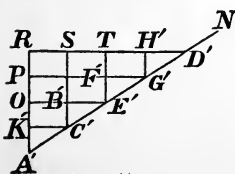
meridians of the points  $A$ ,  $C$ ,  $E$ , and  $G$ , and if  $CK$  be the perpendicular from  $C$  to  $AK$ ,  $EB$  be perpendicular to  $CB$ ,  $GF$  to  $EF$ , and  $DH$  to  $GH$ , then the *departure* for  $AD$  will be  $KC + BE + FG + HD$ , and the *difference of latitude* will be  $AK + CB + EF + GH$ .

11. *Plane sailing* is the art of determining the position of a ship at sea by means of a right-angled plane triangle. Of this triangle the hypotenuse is the distance, the base is the difference of latitude, the perpendicular is the departure, and the angle between the base and the hypotenuse is the course.

When the distance sailed is short, it is evident from the figure that the four quantities mentioned are the parts of a right-angled triangle; for then  $AC$  is the distance,  $AK$  is the difference of latitude,  $KC$  at right angles to  $AK$  is the departure, and  $CAK$  is the course.



If the distance sailed is not short,—as, for instance, the distance  $AD$ ,—then divide it into such a number of small distances,  $AC$ ,  $CE$ ,  $EG$ , and  $GD$ , that each may be considered a straight line. Complete the figure as in the preceding article. Suppose the ship's course to be the same in sailing from  $A$  to  $D$ , then the angles  $CAK$ ,  $ECB$ ,  $GEF$ , and  $DGH$  are equal (Art. 10, (b)).



Now, take any straight line  $A'N$ , and on it lay off  $A'C'$ ,  $C'E'$ ,  $E'G'$ , and  $G'D'$ , equal respectively to  $AC$ ,  $CE$ ,  $EG$ , and  $GD$ , and on these lines  $A'C'$ ,  $C'E'$ ,  $E'G'$ , and  $G'D'$  construct right-angled triangles  $A'K'C'$ ,  $C'B'E'$ ,  $E'F'G'$ ,

and  $G'H'D'$  equal respectively to  $AKC$ ,  $CBE$ ,  $EFG$ , and  $GHD$ , then  $A'D' = AD$ , the distance, and

$A'K' + C'B' + E'F' + G'H' = AK + CB + EF + GH =$  difference of latitude;

$K'C' + B'E' + F'G' + H'D' = KC + BE + FG + HD =$  departure.

Since the ship sails on the same course, the angles  $K'A'C'$ ,  $B'C'E'$ ,  $F'E'G'$ , and  $H'G'D'$  are all equal, and, therefore, the lines  $A'K'$ ,  $C'B'$ ,  $E'F'$ ,  $G'H'$  are parallel; also, the lines  $K'C'$ ,  $B'E'$ ,  $F'G'$ , and  $H'D'$  are parallel (P. and F., 44). Produce  $A'K'$  and  $D'H'$  to meet at  $R$ ; produce  $C'B'$  and  $E'F'$  to meet  $D'R$  at  $S$  and  $T$ ; and produce  $E'B'$  and  $G'F'$  to meet  $A'R$  at  $O$  and  $P$ .  $R$  is a right angle, since it is equal to  $K'$ .  $A'RD'$  is consequently a right-angled triangle.  $A'D'$  represents distance sailed.  $D'A'R$  represents the course.  $A'R$  represents the distance of latitude, for

$$A'R = A'K' + K'O + OP + PR = A'K' + C'B' + E'F' + G'H'.$$

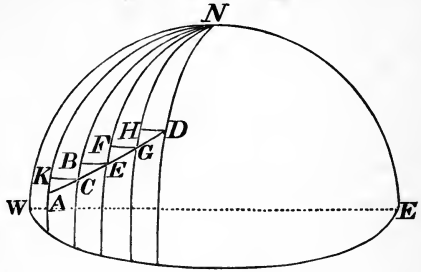
$RD'$  represents the departure, for

$$RD' = RS + ST + TH' + H'D' = K'C' + B'E' + F'G' + H'D'.$$

12. Any two parts of a right-angled triangle being given, in addition to the right angle, the other parts may be found; therefore, of the four quantities, the *distance*, the *course*, the *departure*, and the *difference* of latitude, any two being given, the other two may be found, since these quantities may be represented by the parts of a right-angled triangle, as has been shown in the preceding article, and will, therefore, have the same relation to one another as the corresponding parts of the right-angled triangle.

When the distance is small, this is evident. If the distance is great, it may be divided, as before, into such a number of

small distances,  $AC$ ,  $CE$ ,  $EG$ , and  $GD$ , that each may be considered a straight line. Let the differences of latitude for these small distances be  $AK$ ,  $CB$ ,  $EF$ , and  $GH$ , and let the departures be  $KC$ ,  $BE$ ,  $FG$ , and  $HD$ . As the course is supposed to be the same for the whole distance  $AD$ , the angles  $CAK$ ,  $ECB$ ,  $GEF$ , and  $DGH$  are all equal.



In the right-angled triangle  $AKC$ ,  $\frac{AK}{AC} = \cos CAK = \cos$  course;

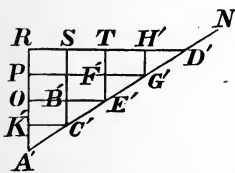
In the right-angled triangle  $CBE$ ,  $\frac{CB}{CE} = \cos BCE = \cos$  course;

In the right-angled triangle  $EFG$ ,  $\frac{EF}{EG} = \cos FEG = \cos$  course; and

In the right-angled triangle  $GHD$ ,  $\frac{GH}{GD} = \cos HGD = \cos$  course.

Therefore (P. and F., 265),

$$(1) \frac{AK + CB + EF + GH}{AC + CE + EG + GD} = \cos \text{course.}$$



Now, if we construct the right-angled triangle  $A'RD'$ , as in the preceding article, having  $A'D' = AD$ , then, as in Art. 11, it may be shown that

$A'R = AK + CB + EF + GH = \text{dif. of latitude}$ , and

$$A'D' = AC + CE + EG + GD = AD = \text{dist.}$$

Substituting these values in (1), we have:

$$\frac{A'R}{A'D'} = \frac{\text{difference of latitude}}{\text{distance}} = \cos \text{course}; \text{ or,}$$

(2) difference of latitude = distance  $\times$  cos course.

In the same manner it can be shown

(3) departure = distance  $\times$  sine of course;

(4) departure = difference of latitude  $\times$  tan course;

and that the other relations shown to hold between the parts of a right-angled plane triangle hold between the quantities in navigation represented by these parts.

**13.** If at a given time it is required to find the position of a ship by *plane sailing*, the rate of speed per hour at which she is sailing is first ascertained. This rate, multiplied by the number of hours elapsed since the last ascertained position, will give the *distance* from that position. The angle made by the direction in which the ship is headed, and the N. and S. line of the mariner's compass (with correction, if necessary), will furnish the *course*. From these data the *difference of latitude* and the *departure* are found (Art. 12, (2) and (3)), and thus the position of the ship is known.

For example, suppose the average rate of sailing is ascertained to be 9 miles an hour, and that 12 hours have elapsed since the last ascertained position, then the distance is 108. If the course is observed to be N.  $30^\circ$  E., the ship's position N. of her last position will be, in miles,  $108 \times \cos 30^\circ$ , or 93.5 miles, and her position E. will be  $108 \times \sin 30^\circ$ , or 54 miles.

**14.** The rate of sailing is ascertained by means of the *log*.

The *log*, in one of its simplest forms, is a triangular piece of wood, so weighted as to assume, when attached to its line and placed in water, a position calculated to oppose the most resist-

ance to force applied to the line. The *line* is a rope knotted at regular intervals.

When the log is thrown overboard and the line is reeled out by the forward motion of the ship, the number of knots passing over a given point in a given period of time will give the rate of sailing for that period of time. Moreover, *if the interval between the knots be the same part of a mile that the period of time is of an hour, the number of knots passed out during the period of time will give the number of miles per hour sailed by the ship.*

For instance, let the period of time be  $\frac{1}{2}$  minute or  $\frac{1}{120}$  hour, then the interval between the knots must be  $\frac{1}{120}$  mile. Suppose, then, 4 such knots (counting the intervals by the knots) should be reeled out by the forward motion of the ship during  $\frac{1}{2}$  minute, we should find the distance sailed per hour (that is, the rate per hour) by the proportion

$$\frac{1}{2} \text{ min.} : 60 \text{ min.} :: \frac{4}{120} \text{ mile} : x \text{ (the distance per hour).}$$

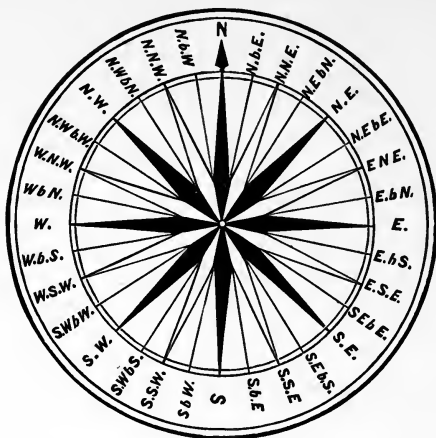
$\therefore x = 2 \times 60 \times \frac{4}{120} = 4$  miles, the same number of miles per hour as knots per half minute.

15. The *mariner's compass* consists of a circular card attached to a magnetic needle, which generally points N. and S.\* Each quadrant of this card is divided into eight equal parts, called points, to which names are given as represented in the accompanying figure.†

\* The magnetic needle does not at all places on the earth's surface point N. and S. Charts for the use of navigators, however, give the amount of variation for places where the needle is subject to variation, so that for such places a correction can be applied to the direction indicated by the needle, so as to obtain a true N. and S. line.

† The naming of the points in each quadrant will be seen to be not without method. Thus, in the quadrant between N. and E., the point midway between N. and E. takes its name from both these points; then the point midway between N. and N.E., and the point midway between

Also, to express courses between the points, the points are subdivided into half points and quarter points.



The points are read (taking the quadrant between the N. and E. points), North by East, North North East, North East by North, North East, etc., etc.

The angle between two adjacent points is  $\frac{90}{8}^{\circ}$ , or  $11^{\circ} 15'$

**16.** Distance, departure, and difference of latitude are all expressed in *nautical miles*.

E. and N.E., take their names respectively from the two points between which each is situated, as one of these is north and the other is east of N.E.

The remaining points are named from the nearest *main* point (calling N., E., and N.E. main points), with the addition of N. or E. as the point to be named is north or east of this nearest point, with the word *by* placed between the two. Thus, the point between N. and N.N.E. is N. *by* E.; the point between N.N.E. and N.E. is N.E. *by* N.; the point between N.E. and E.N.E. is N.E. *by* E.; and the point between E.N.E. and E. is E. *by* N.

The points of the other quadrants may be shown to be named on the same method.



A *nautical mile* is equal to a minute of an arc of the circumference of a great circle of the earth.

As there are 69.115 *common* miles in a degree of such an arc (Trig., Art. 173, Ex. 5), a nautical mile is *longer* than the common statute mile.

Differences of latitude expressed in degrees and minutes is, therefore, easily converted into miles, or, when expressed in nautical miles, is easily changed into degrees and minutes.

Thus,  $5^{\circ} 33'$  difference of latitude = 333 miles; and 656 miles difference of latitude =  $10^{\circ} 56'$ .

Ex. 1. A ship sails N.E. b. N. a distance of 70 miles. Required her departure and difference of latitude at the end of that distance. The course is 3 points from N. toward E., and is, therefore,  $3 \times (11^{\circ} 15')$  or  $33^{\circ} 45'$ .

*Ans.* Dep. = 38.89 miles; dif. lat. = 58.2 miles.

Ex. 2. A ship from lat.  $33^{\circ} 5' N.$  sails S.S.W. 362 miles. Required her departure and the latitude arrived at.

*Ans.* Dep. = 138.5 miles; lat.  $27^{\circ} 30.6' N.$

Ex. 3. A ship, leaving port in lat.  $42^{\circ} N.$ , sails S.  $37^{\circ} W.$  till her departure is 62 miles. Required the distance sailed and the latitude arrived at. *Ans.* Dist. = 103 miles; lat.  $40^{\circ} 38' N.$

Ex. 4. A ship sails S.  $50^{\circ} E.$  from lat.  $7^{\circ} N.$  to lat.  $4^{\circ} S.$  Required her distance and departure.

*Ans.* Dist. = 1026.78 miles; dep. = 786.56 miles.

Ex. 5. A ship sails from the equator on a course between S. and W. to lat.  $5^{\circ} 52' S.$ , when her departure is found to be 260 miles. Required her course and the distance sailed.

*Ans.* Course = S.  $36^{\circ} 27' W.$ ; dist. = 437.6 miles.

Ex. 6. A ship sails from lat.  $3^{\circ} 2' N.$  on a course between N. and W. a distance of 382 miles, when her departure is found to be 150 miles. Required her course and the latitude arrived at.

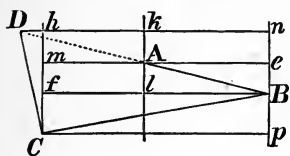
*Ans.* Course = N.  $23^{\circ} 7\frac{1}{4}' W.$ ; lat.  $8^{\circ} 53' N.$

17. A *traverse* is the path described by a ship which changes its course from time to time.

The object of *traverse sailing* is to find the position of a ship at the end of a traverse; the *distance* sailed from the position left to the position reached; and the *course* for this distance.

The method of accomplishing this object will best be seen by means of an example.

Suppose a ship to start from  $A$  and sail to  $B$ , then from  $B$  to  $C$ , and then from  $C$  to  $D$ . It is required



to find her position at  $D$ ; that is, to find the difference of latitude and the departure made in going from  $A$  to  $D$ . These quantities being found, the distance  $AD$ , and the course  $DAk$ , can be calculated.

(REMARK. — The distances  $AB$ ,  $BC$ , and  $CD$  are all supposed, in traverse sailing, to be short distances, and therefore are to be treated, like similar distances in plane sailing, as straight lines.)

Through  $B$ ,  $A$ , and  $C$  suppose meridians  $pn$ ,  $lk$ , and  $Ch$ , and through  $B$ ,  $A$ ,  $C$ , and  $D$  parallels of latitude  $Bf$ ,  $me$ ,  $Cp$ , and  $Dkn$  to be drawn.

$Ak$  is the difference of latitude of  $AD$ , and  $kD$  is the departure of  $AD$ .

$$(1) Ak = mh = Ch - Cm = Ch - (Cf + fm) = Ch - (Bp + eB).$$

Now,  $Ch$  is a north latitude, and  $Bp$  and  $eB$  are south latitudes, therefore, the difference of latitude of  $AD$  is equal to the difference between the  $N.$  latitude of one distance of the traverse and the sum of the  $S.$  latitudes of the other distances.

$$(2) \quad kD = nD - kn = nh + hD - Ae = pC + hD - Ae.$$

But  $pC$  and  $hD$  are west departures, and  $Ae$  is an east departure; therefore, the departure for  $AD$  is equal to the difference between the sum of the *west* departures of two distances of the traverse and the *east* departure of the third distance.

In the case given above, the number of the parts of the traverse is only three, but if a fourth distance on a course between N. and E. were given, a second north latitude and a second east departure would enter our figure, so that the *difference of latitude* between the *first* and *last* position of the ship would, in that case, be *equal to the difference between the sum of the north latitudes and the sum of the south latitudes*; and the departure, in passing directly from the first to the last position, would be *equal to the difference between the sum of the east departures and the sum of the west departures*. The same principle would hold true for a traverse of any number of distances greater than four. The proof would be similar to that given above for a traverse of three distances.

The principle stated may, therefore, be taken as a *general* one.

Ex. 1. Suppose a ship sailing on a traverse makes courses and distances as follows: from  $A$  to  $B$ , E. b. S. 16 miles; from  $B$  to  $C$ , W. b. S. 30 miles; and from  $C$  to  $D$ , N. b. W. 14 miles. Required the distance from  $A$  to  $D$  and the course for that distance. Before solving these examples the student is advised to plot the figures for them by means of a protractor and a plane scale.

	COURSE	DISTANCE	N.	S.	E.	W.
1	S. 78° 45' E.	16		3.12	15.69	
2	S. 78° 45' W.	30		5.85		29.42
3	N. 11° 15' W.	14	13.73			2.73
Sum			13.73	8.97	15.69	32.15
			<u>8.97</u>			<u>15.69</u>

$$\text{dif. of lat.} = 4.76 \text{ N.} \qquad \text{dep.} = 16.46 \text{ W.}$$

∴ (In the figure, page 22)  $Ak = 4.76$ , and  $kD = 16.46$ .

$$\text{Course} = kAD. \quad \frac{kD}{Ak} = \frac{16.46}{4.76} = \tan. 73^\circ 52' 15'' = \tan. kAD$$

∴ *Course* = N. 73° 52' 15" W., or N. 73° 52' W., as the result is generally given only to the nearest minute.

$$\text{Dist.} = AD = \frac{kD}{\sin DAK} = \frac{16.46}{\sin 73^\circ 52'} = 17.13 \text{ miles.}$$

Ex. 2. A ship sails on a traverse, making the following courses and distances: S.E., 25 miles; E.S.E., 32 miles; E., 17 miles; N. b. W., 63 miles. Required the distance from her first to her last position, and the course.

$$\text{Ans. Dist.} = 60.94 \text{ miles; course} = \text{N. } 58^\circ 29' \text{ E.}$$

Ex. 3. A ship sails on a traverse, making the following courses and distances: N.E., 25 miles; E.S.E., 40 miles; E. b. N., 35 miles; N. b. W., 33 miles. Required the course and distance from her first position to her last position.

$$\text{Ans. Course} = \text{N. } 63^\circ 16' \text{ E.; dist.} = 92.41 \text{ miles.}$$

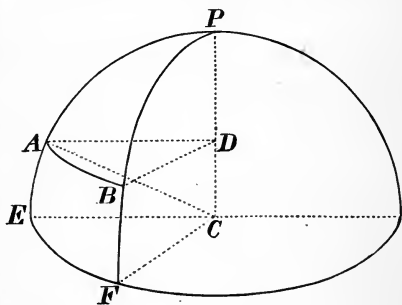
18. *Parallel sailing* is sailing on a parallel of latitude. In parallel sailing, therefore, a ship sails east or west (Art. 4, (a)). The *distance* is the same as her *departure*, and the *difference of latitude* disappears.

The problem in parallel sailing is to convert *dis-*

tance on a parallel into difference of longitude; that is, given a distance between two meridians measured on a parallel of latitude, to find from it the distance between the same meridians measured on the equator (Art. 5, (b)).

The method of solving this problem will be understood by means of the accompanying figure, which represents a part of the earth.

In this figure let  $C$  represent the center of the earth;  $P$  be one of the poles;  $EF$  a part of the equator,  $CE$  and  $CF$  its radii;  $AB$  a part of a parallel of latitude intercepted between two meridians,  $PAE$  and  $PBF$ ; and let  $DA$  and  $DB$  be the radii of this parallel.



Draw the radius  $AC$ .

$$\frac{AB}{EF} = \frac{AD}{EC} = \frac{AD}{AC} = \cos DAC = \cos ACE.$$

But  $ACE$  is the latitude of  $A$  (Art. 6), or of the parallel  $AB$ .

$$\begin{aligned} \therefore \frac{\text{distance on parallel between two meridians}}{\text{distance on equator between same meridians}} \\ = \cos \text{ lat. of parallel,} \end{aligned}$$

Or, expressing this in other terms,

$$(1) \quad \frac{\text{dist. on a parallel}}{\text{dif. of longitude}} = \cos \text{ lat. of parallel.}$$

$$(2) \quad \therefore \text{ dif. of longitude} = \frac{\text{dist. on parallel}}{\cos \text{ lat. of parallel}}$$

$$= \text{dist. on parallel} \times \sec \text{ lat.}$$

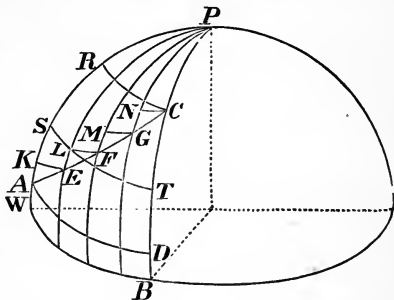
19. Since for a short distance departure is measured on a parallel of latitude (Art. 10, (c)), in (1) of last article substituting departure for distance on a parallel, we have

$$(1) \quad \text{departure} = \text{dif. of long.} \times \cos \text{ lat.}; \text{ and}$$

$$(2) \quad \text{dif. of long.} = \frac{\text{departure}}{\cos \text{ lat.}} = \text{departure} \times \sec \text{ lat.}$$

20. In plane sailing, when the distance sailed is short, the departure can be converted into difference of longitude by formula (2) of the preceding article, or, when the difference of longitude is given, it can be changed into departure by formula (1); in both cases the parallel of latitude being supposed to be known. But if the distance is not short, there is danger of error, since the latitude varies from point to point of the distance, and the departure is neither the distance on a parallel through the point from which the ship sails, nor on a parallel through the point arrived at. This will be understood from the figure.

Suppose the figure to represent a part of the earth's surface, and that  $AC$  represents the distance sailed by a ship. The departure for that distance would be  $KE + LF + MG$ , etc. (Art. 10, (c)), which is, evidently, equal to neither  $AD$  nor  $RC$ , since, as the meridians  $PE, PF$ , etc., meet at the pole  $P$ , the distance between them measured on a parallel diminishes as we proceed from the equator. The total departure is consequently less than  $AD$  and



greater than  $RC$ . It would, also, be incorrect to convert this departure into difference of longitude by using the latitude of  $RC$  or the latitude of  $AD$ , as we really ought to use the latitude of the part departure,  $KE$  for  $KE$ , the latitude of  $LF$  for  $LF$ , etc., and then take the sum of the differences of longitude corresponding to these departures for the whole difference of longitude. If this method were practicable, and we could make the distances  $AE, EF$ , etc., small enough, we should find the difference of longitude without appreciable error. As this method is not practicable, two other methods are used for changing departure into difference of longitude. One is the method of *middle latitude sailing*, the other is the method of *Mercator's sailing*.

21. In *middle latitude sailing*, departure is converted into difference of longitude by using, in Art. 19, (2), the latitude, whose parallel is midway between the parallel of the point sailed from and the parallel of the point arrived at.

This latitude is equal to the *half sum* of the latitude sailed from and the latitude arrived at, if both

latitudes are on *the same side* of the equator, but to the half *difference*, if *one* is *north* and the *other south* of the equator.

Thus, suppose  $ST$  is the parallel midway between  $RC$  and  $AD$ ; that is, suppose  $AS = SR$ ,  $A$  and  $C$  being both north of the equator.  $WS$  is the measure of the latitude of the parallel  $ST$  (Art. 6).

$$WS = \frac{2(WA + AS)}{2} = \frac{WA + WR}{2}.$$

In a similar manner it may be shown that, in case one place is north and the other south of the equator, the middle latitude is half the difference of the latitudes of the two places.

The method of middle latitude sailing is not perfectly exact, but is made nearly so by applying corrections taken from a table prepared for that purpose.\* For short distances or for sailing near the equator it is practically correct.

22. By Art. 19,

$$(1) \quad \text{dep.} = \text{dif. of long.} \times \cos \text{ lat.},$$

$$\text{and } (2) \quad \text{dif. of long.} = \frac{\text{dep.}}{\cos \text{ lat.}} = \text{dep.} \times \sec \text{ lat.}$$

In middle latitude sailing, for latitude we substitute mid. lat., and (1) becomes

$$(a) \quad \text{dep.} = \text{dif. of long.} \times \cos \text{ mid. lat.},$$

and (2) becomes

$$(b) \quad \text{dif. of long.} = \frac{\text{dep.}}{\cos \text{ mid. lat.}} = \text{dep.} \times \sec \text{ mid. lat.}$$

Equations (a) and (b) can be represented in terms of base and hypotenuse of a right-angled triangle.

\* Table of Corrections to Middle Latitude, pages 172, 173.



This triangle can be combined in one figure with the triangle for plane sailing, as will be seen by the accompanying diagram.

Ex. 1. From lat.  $40^{\circ}$  N. and long.  $50^{\circ}$  W. a vessel sails on a course N.W. b. N. to lat.  $50^{\circ} 12'$  N. Required distance sailed, and the longitude of point of arrival.

$$AB = 10^{\circ} 12' = 612.$$

$$\text{Angle } A = 33^{\circ} 45'.$$

Angle  $DCB$

$$= \text{mid. lat.} = \frac{40^{\circ} + 50^{\circ} 12'}{2}$$

$$= 45^{\circ} 6' + \text{cor}^* \text{ of } 2' = 45^{\circ} 8'.$$

$$AC = \text{dist.} = \frac{AB}{\cos A} = \frac{612}{\cos 33^{\circ} 45'}$$

$$L. = 2.78675$$

$$L. = 9.91985$$

$$\log 736.3 = 2.86690$$

$$\text{dist.} = 736.3 \text{ miles.}$$

$$BC = \text{dep.} = AB \tan A = 612 \tan 33^{\circ} 45'.$$

$$CD = \text{dif. of long.} = \frac{BC}{\cos DCB} = \frac{612 \tan 33^{\circ} 45'}{\cos 45^{\circ} 8'}$$

$$\log 612 = 2.78675$$

$$\log \tan 33^{\circ} 45' = 9.82489$$

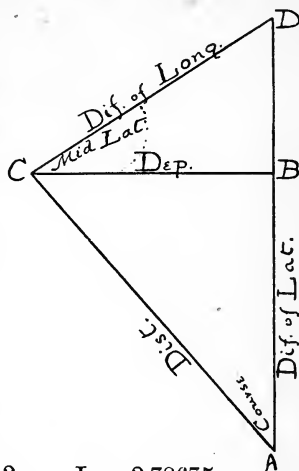
$$\text{colog. } \cos 45^{\circ} 8' = 0.15153$$

$$\log 579.7 \quad 2.76317$$

$$\text{dif. of long.} = 579'.7 \text{ W.} = 9^{\circ} 39'.7 \text{ W.}$$

$$\text{long. of pt. of departure} = 50^{\circ} \quad \text{W.}$$

$$\text{long. of pt. of arrival} = 59^{\circ} 39'.7 \text{ W.}$$



\* Table of Corrections to Middle Latitude, pages 172, 173.

**Ex. 2.** From lat.  $32^{\circ} 22' N.$ , long.  $64^{\circ} 38' W.$ , a ship sails S.W. by W. a distance of 375 miles. Required the latitude and longitude of point of arrival.

*Ans.*  $28^{\circ} 53'.7 N.$ ;  $70^{\circ} 38'.6 W.$

**Ex. 3.** From lat.  $40^{\circ} 28' N.$ , long.  $74^{\circ} 1' W.$ , a ship sails S.E. b. S. a distance of 450 miles. Required the latitude and longitude of point of arrival.

*Ans.*  $34^{\circ} 13'.8 N.$ ;  $68^{\circ} 47'.5 W.$

**Ex. 4.** From lat.  $40^{\circ} 28' N.$ , long.  $74^{\circ} 1' W.$ , a ship sails S.E. b. E. to lat.  $31^{\circ} 10' N.$  Required the distance sailed and longitude of point of arrival.

*Ans.* 1004 miles;  $56^{\circ} 53'.5 W.$

**Ex. 5.** From lat.  $32^{\circ} 28' N.$ , long.  $64^{\circ} 48' W.$ , a vessel sails on a course between S. and W. to lat.  $28^{\circ} 54' N.$ , making a distance of 475 miles. Required the course and the longitude of the point of arrival.

*Ans.* S.  $63^{\circ} 13' 22'' W.$ ;  $72^{\circ} 59' W.$

**Ex. 6.** If from lat.  $46^{\circ} 40' N.$ , long.  $53^{\circ} 7' W.$ , a ship sails to lat.  $32^{\circ} 38' N.$ , long.  $16^{\circ} 40' W.$ , required the course and distance sailed.

*Ans.* S.  $63^{\circ} 23' E.$ ; 1879 miles.

**23.** In *Mercator's sailing* departure is converted into difference of longitude by means of the principles of Mercator's chart.

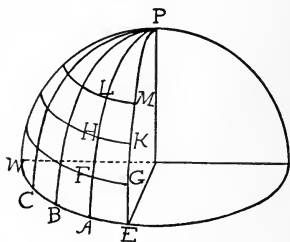
As the meridians all pass through the poles, a chart, in order to represent correctly the earth's surface, should make the meridian lines curved and approaching one another toward either pole. The parallels of latitude being circles smaller and smaller the nearer they are to the poles, should, on a correct chart, be shorter and shorter curves the farther they are from the equator.

On Mercator's chart the equator, the meridians, and parallels of latitude are all represented as *straight* lines. Meridian lines are all drawn at right angles to

the equator, and are, therefore, parallel to each other. Parallels of latitude are made parallel to the equator, and therefore, like parts of any parallel, are equal to like parts of the equator. On Mercator's chart, therefore, the east and west dimensions of any part of the earth's surface are made too large, except near the equator. To preserve the true proportion existing between the dimensions of any particular part of the earth, the north and south dimensions are lengthened in proportion to the lengthening of the east and west dimensions. The method of accomplishing this will be understood by means of the accompanying figures.

On a globe representing the earth, the meridians  $PE$ ,  $PA$ , etc., make with the equator and with parallels of latitude a number of quadrilaterals, all of whose sides are curved lines.

Thus, in the figure, if the equator, represented by  $WE$ , be supposed to be divided into a number of parts of  $10^\circ$ , each equal to  $AE$ , and on the meridian  $PE$ , we lay off  $EG$ ,  $GK$ ,  $KM$ , etc., each

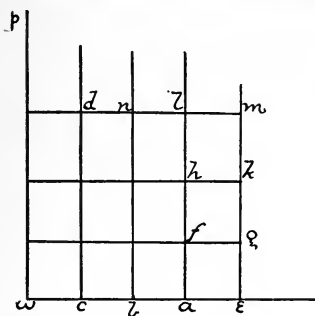


also equal to  $10^\circ$ , drawing parallels of latitude through the points of division  $G$ ,  $K$ ,  $M$ , etc., we should divide the surface of the globe into several tiers of quadrilaterals; one tier composed of quadrilaterals each equal to  $FGAE$ , a second tier of quadrilaterals each equal to  $HFGK$ , a third tier of figures each equal to

*LHKM*, etc. Supposing the earth to be a sphere, on the globe representing it, *AE*, *EG*, *GK*, and *KM* would all be equal, as they are equal parts of equal great circles. Also, the ratio of *EG* to *GF* = sec 10° (Art. 18, (2)), and

$$\frac{GK}{KH} = \sec 20^\circ; \quad \frac{KM}{ML} = \sec 30^\circ.$$

If we desire to represent these various tiers of quadrilaterals on Mercator's chart, with the features of the earth which they inclose, we draw a straight line of the same length as the curved line representing the equator on the globe; that is, we make *we* equal to *WE*, and divide it into parts *wc*, *cb*, *ba*, and



*ae*, each equal to *AE*, and at the points *w*, *c*, *b*, *a*, and *e* erect perpendiculars *wp*, *cd*, *bn*, etc., to represent the meridians *PW*, *PC*, *PB*, etc. The lines *wp*, *cd*, *bn*, etc., being at right angles to *we*, are parallel. If we draw a series of lines parallel to *we* to represent parallels of latitude, as *dm*,

*hk*, and *fg*, we form tiers of rectangles; one tier of rectangles each equal to *fgea*, a second tier of rectangles each equal to *hkgf*, and so on. By this construction *fg*, *hk*, and *bn* are all made equal to *ae*. To make the quadrilaterals, like *fgea*, represent the corresponding quadrilaterals, like *FGEA*, we must

lengthen  $eg$  as much as we have lengthened  $fg$ . We have made

$$fg = ae = AE = FG \sec 10^\circ \text{ (Art. 18, (2))},$$

therefore we must make

$$eg = EG \sec 10^\circ \text{ (or, } ae \sec 10^\circ),$$

so that

$$\frac{eg}{gf} = \frac{EG}{GF}.$$

Consequently, if on the line  $em$  we take a point  $g$  so that  $eg = ae \sec 10^\circ$ , and through  $g$  draw a straight line parallel to  $wae$ , we shall form a tier of quadrilaterals each equal to  $afge$ , whose sides  $af$  and  $eg$  have the same ratio to  $fg$  which  $AF$  and  $EG$  bear to  $FG$ . In like manner, if we make  $gk = ae \sec 20^\circ$ , and through  $k$  draw another straight line parallel to  $wae$ , we shall form a second tier of quadrilaterals each equal to  $fhkg$ , whose sides  $fh$  and  $gk$  have the same ratio to  $hk$  which  $FH$  and  $GK$  bear to  $HK$ . Through  $m$ , if  $km = ae \sec 30^\circ$ , we draw another straight line parallel to  $wae$ , making a third tier of quadrilaterals, and so on for the rest of the chart.

If, instead of taking the parts, like  $ae$ , equal to  $10^\circ$  of the equator we make them  $1^\circ$  or  $1'$ , then the parallels of latitude will be drawn at smaller intervals on the meridian  $me$ .

If  $ae = 1'$ ,

then  $em = 1' (\sec 1' + \sec 2' + \sec 3')$ .

In the same way the length of Mercator's meridian up to  $30^\circ$  would equal the sum of

$$\sec 1' + \sec 2' + \sec 3' \cdots + \sec 29^\circ 59' + \sec 30^\circ,$$

or the sum of the series of secants, from  $\sec 1'$ , increasing by intervals of  $1'$  up to  $\sec 30^\circ$ .

Mercator's chart is, therefore, a chart of the earth's surface on which the unit of the scale of representation is continually changing. Near the equator the parts of the earth's surface are correctly represented. As we go north or south to any distance from that line, the parts of the earth are enlarged, as compared with the parts near the equator.

As the earth is not a perfect sphere, but a spheroid with its shorter diameter connecting the poles, the meridians are all smaller curves than the equator, so that in the later Mercator's charts, and in the tables of the lengths of Mercator's meridians for different latitudes (called Tables of Meridional Parts), this fact is taken into account. However, with this modification, the method of construction of a Mercator's chart just given is substantially correct.

In Mercator's sailing the unit of measure, or the nautical mile, is  $1'$  of the equator. Tables of Meridional Parts accordingly give in minutes, or nautical miles, the length of Mercator's meridian from the equator to any point of latitude denoted by the table.

**24.** The path of a ship continuing on the same course is, on Mercator's chart, a *straight* line, since to continue on the same course the ship must cut each

of the meridians at the same angle, and the meridians are parallel straight lines.

As Mercator's meridian is longer than the true meridian on a chart representing a curved surface, and is continually lengthening, the *number of parts* in a certain number of degrees and minutes of the table will generally be greater than the number of *minutes* in the corresponding number of degrees and minutes of true meridian.

Thus, for example, the number of parts of  $16^\circ$  of the table of meridional parts is 966.4, while the number of minutes of  $16^\circ$  of true meridian is 960.

Near the equator the number of minutes of true meridian is greater than the number of meridional parts of the same degree measure.

Thus,  $4^\circ$  of true meridian =  $240'$ , while meridional parts of  $4^\circ = 238.6$ .

(a) *Meridional difference of latitude* is the distance on Mercator's meridian between two parallels of latitude.

Where the latitudes of two places are given, the *meridional difference of latitude* is found by taking the *meridional parts* of the less latitude from the *meridional parts* of the greater, if *both* are *north*, or *both* are *south* latitudes; but, by *adding* the meridional parts of the two latitudes, if *one* is *north* and the *other* *south* latitude.

The rule is the same as for finding the true difference of latitude, except that *meridional parts* of latitude are used instead of latitude.

## Ex. 1.

lat. of Newport, R.I., is $41^{\circ} 29' \text{ N.}$	merid. parts 2725.0
---	---------------------

lat. of Savannah, Ga., is $32^{\circ} 5' \text{ N.}$	merid. parts 2022.1
--	---------------------

dif. of lat. $9^{\circ} 24'$	merid. dif. lat. 702.9
------------------------------	------------------------

## Ex. 2.

lat. of Pato Island is $10^{\circ} 38' \text{ N.}$	merid. parts 637.5
--	--------------------

lat. of Cape St. Roque is $5^{\circ} 29' \text{ S.}$	merid. parts 327.3
--	--------------------

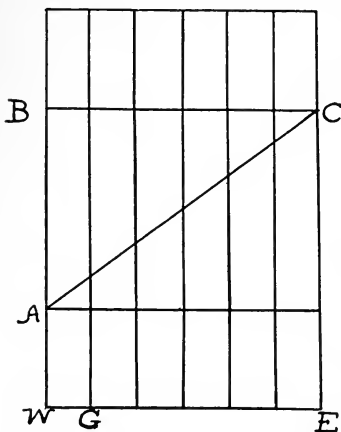
dif. of lat. $16^{\circ} 7'$	merid. dif. lat. 964.8
------------------------------	------------------------

If one latitude is given, and the meridional difference of latitude is found, the latitude required is found by *adding* the meridional parts of the given latitude to the meridional difference of latitude, if the place whose latitude is required is farther from the equator than the place whose latitude is given, and if both places are on the same side of the equator; but, by *subtracting* the meridional difference of latitude from the meridional parts of the given latitude if the place whose latitude required is nearer the equator than the place whose latitude is given; the degrees

and minutes, answering to the result as found in the table of meridional parts, will be the latitude required.

This will be evident from the figure, in which *WE* represents the equator on Mercator's chart.

If the latitude of *A* is given, the meridional parts, or the distance *AW*, can be found from the table. *AB* being the merid-





ional difference of latitude, the meridional parts of  $C$  or the distance,  $EC = WB = WA + AB$ .

If the latitude  $C$  is given, then from the table  $CE (=WB)$  is found; then,  $AW = WB - AB = CE - AB$ .

Ex. 1. lat. of place left is  $25^{\circ} 6' N$ . merid. parts = 1546.9  
 ship sails northerly till she makes merid. dif. of lat. 750.0  
 meridional parts of place arrived at = 2296.9

Therefore, from table, latitude arrived at is (nearly)  $35^{\circ} 54' N$ .

Ex. 2. lat. of place left is  $46^{\circ} 10' S$ . merid. parts = 3113.4;  
 ship going northerly, her merid. dif. of lat. is found

to be . . . . . = 825.6  
 merid. parts of lat. arrived at = 2287.8

Therefore, latitude arrived at is  $35^{\circ} 46'.4 S$ .

If a ship starting from one side of the equator sails to a point on the other side, the latitude of the point arrived at is found by subtracting the meridional parts of the given latitude from the meridional difference of latitude; the result will be the meridional parts of the required latitude.

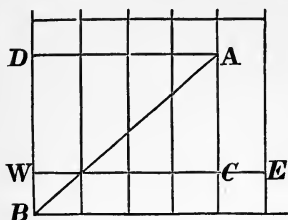
Ex. The meridional difference of latitude is . . . 1805.8  
 which is made by a ship going *north*, starting from lat.

$8^{\circ} 41' S$ . . . . . merid. parts = 519.5

Therefore, latitude arrived at is  $21^{\circ} 5' N$ . Merid. parts 1286.3

It is evident, therefore, if the meridional difference of latitude made by a ship sailing *from* a point on either side of the equator *toward* a point on the opposite side, exceeds the meridional parts of the latitude left, that the ship has crossed the line and has arrived at a N. latitude, if the latitude left was S., but has arrived at a S. latitude if the latitude left was N.

Thus, on the figure,  $WE$  representing the equator, a ship

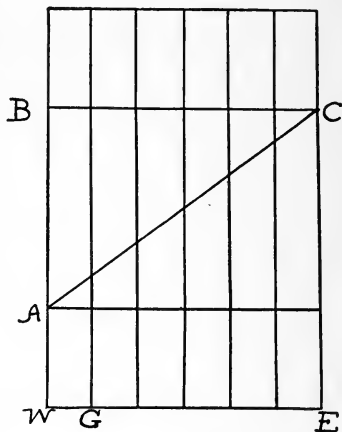


sails from  $B$  toward  $A$ .  $BW$  represents the meridional parts of the latitude left,  $BD$  is the meridional difference of latitude,  $AC$  represents the meridional parts of the latitude arrived at.

$$AC = WD = BD - BW.$$

### 25. Combining Mercator's sailing with plane sailing.

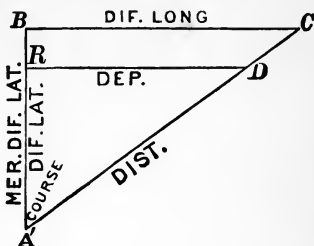
Let the figure represent a part of Mercator's chart, on which  $WE$  represents the equator, and  $AC$  is the lengthened distance between two points  $A$  and  $C$ .  $CAB$  is the course for that distance. If, from  $C$ ,  $CB$  be drawn perpendicular to the meridian  $WB$ ,  $AB$  will be the meridional difference of latitude, and  $BC$  will be the lengthened departure (Art. 10, (c)).



Now,  $BC = WE$ ; that is, *departure*, on Mercator's chart, equals *difference of longitude* (Art. 5, (b)).

If, in plane sailing, the same course and distance were represented by the hypotenuse and acute angle of a right-angled triangle,  $A'RD$ ,  $A'R$  would be true difference of latitude,  $RD$  would be *departure*.

Now,  $ABC$  and  $A'RD$  are similar triangles, since the angles  $A'$  and  $A'$  are equal, as they both represent the same course, and the angles  $R$  and  $B$  are right angles. Placing the angle  $A$  upon  $A'$ , the two triangles may be combined, as in the figure; then



$$\frac{A'R}{A'B} = \frac{RD}{BC}; \text{ that is,}$$

$$(1) \frac{\text{dif. of lat.}}{\text{merid. dif. of lat.}} = \frac{\text{dep.}}{\text{dif. of long.}}$$

Also,  $BC = A'B \times \tan A'$ ; that is,

$$(2) \text{ dif. of long.} = \text{merid. dif. of lat.} \times \tan \text{course.}$$

By means of these two triangles all cases of Mercator's sailing may be solved, and the position of a ship at sea may be determined from the usual data.

The latitude of one position of the ship, either of the point left or the point arrived at, must always be known in order to use Mercator's sailing.

The line  $A'C$  is not required in calculations.  $A'D$  represents the true distance.

Ex. 1. A ship starting from lat.  $37^\circ$  N., long.  $10^\circ$  W., sails on a course between N. and E. to lat.  $41^\circ$  N., making a distance of 300 miles. Required the course and the longitude arrived at.

lat. $41^\circ$ N.	merid. parts = 2686.5
lat. $37^\circ$ N.	merid. parts = 2378.8
dif. of lat. = $4^\circ = 240'$	merid. dif. of lat. = 307.7

Taking the figure of the preceding article,  $A'D = 300$ ,  $A'R = 240$ , and  $A'B = 307.7$ .

$$\frac{A'R}{A'D} = \frac{240}{300} = \cos A' = \cos \text{course.} \quad BC = A'B \times \tan A'.$$

$$\text{dif. long.} = 307.7 \times \tan 36^\circ 52' 12''$$

$$\log 240 = 2.38021$$

$$\log 307.7 = 2.48813$$

$$\log 300 = \underline{2.47712}$$

$$\log \tan 36^\circ 52' 12'' = \underline{9.87506}$$

$$\log \cos 36^\circ 52' 12'' \cdot \underline{9.90309}$$

$$\log 230.8 \quad \underline{2.36319}$$

$$\text{course} = \text{N. } 36^\circ 52' \text{ E.}$$

$$\text{dif. long.} = 3^\circ 50'.8 \text{ E.}$$

$$\text{long. left, } 10^\circ \text{ W.}$$

$$\text{dif. of long. } \underline{3^\circ 50'.8 \text{ E.}}$$

$$\text{long. arrived at} = \underline{6^\circ 9'.2 \text{ W.}}$$

Ex. 2. A ship leaving lat.  $50^\circ 10' \text{ N.}$ , long.  $60^\circ \text{ E.}$ , sails E. S. E. till her departure is 957 miles. Required latitude and longitude arrived at, and the distance sailed.

$$\frac{957}{\sin 67^\circ 30'} = \text{dist.}^*$$

$$\frac{957}{\tan 67^\circ 30'} = \text{dif. of lat.}$$

$$\log 957 = 2.98091$$

$$\log 957 = 2.98091$$

$$\log \sin 67^\circ 30' = \underline{9.96562}$$

$$\log \tan 67^\circ 30' = \underline{10.38278}$$

$$\log 1035.8 \quad \underline{3.01529}$$

$$\log 396.4 = \underline{2.59813}$$

$$\text{dist.} = 1035.8 \text{ miles.}$$

$$\text{dif. lat.} = 6^\circ 36'.4 \text{ S.}$$

$$\text{lat. left} = \underline{50^\circ 10' \text{ N.}}$$

$$\text{lat. reached} = \underline{43^\circ 33'.6 \text{ N.}}$$

$$\text{merid. parts of } 50^\circ 10' = 3472.4$$

$$\text{merid. parts of } 43^\circ 33'.6 = \underline{2893.4}$$

$$\text{merid. dif. of lat.} = 579$$

$$\text{dif. long.} = 579 \times \tan 67^\circ 30'.$$

$$\log 579 = 2.76268$$

$$\text{dif. long.} = 23^\circ 17'.8 \text{ E.}$$

$$\text{long. tan } 67^\circ 30' = \underline{10.38278}$$

$$\text{long. left} = \underline{60^\circ \text{ E.}}$$

$$\log 1397.8 = \underline{3.14546}$$

$$\text{long. reached} = \underline{83^\circ 17'.8 \text{ E.}}$$

\* No figure is given for this example, but the student is advised to plot the figure for it, and the figure for each of the examples which follow.

**Ex. 3.** From a point in lat.  $49^{\circ} 57' N.$ , long.  $5^{\circ} 14' W.$ , a vessel sails on a course  $S. 39^{\circ} W.$  to a point in lat.  $45^{\circ} 31' N.$  Required the distance sailed and the longitude reached.

*Ans.* Dist. = 342.28 miles; long. =  $10^{\circ} 33'.5 W.$

**Ex. 4.** From a point in lat.  $49^{\circ} 57' W.$ , long.  $5^{\circ} 14' W.$ , a vessel goes to lat.  $39^{\circ} 20' N.$ , making a  $W.$  departure of 789 miles. Required the course sailed, the distance made, and the longitude reached.

*Ans.* Course =  $S. 51^{\circ} 7' W.$ ; dist. = 1014 miles; long. =  $23^{\circ} 43'.8 W.$

**Ex. 5.** From a point in lat.  $14^{\circ} 45' N.$ , long.  $17^{\circ} 33' W.$ , a vessel sails  $S. 28^{\circ} 7\frac{1}{2}' W.$  to a point in long.  $29^{\circ} 26' W.$  Required the latitude reached and the distance sailed.

*Ans.* Lat. reached =  $7^{\circ} 26'.5 S$ ; dist. = 1509.8 miles.

**Ex. 6.** From a point in lat.  $20^{\circ} 22' N.$ , long.  $45^{\circ} 24' W.$  to a point in lat.  $40^{\circ} 30' N.$ , long.  $20^{\circ} 10' W.$ , it is required to find the course and distance.

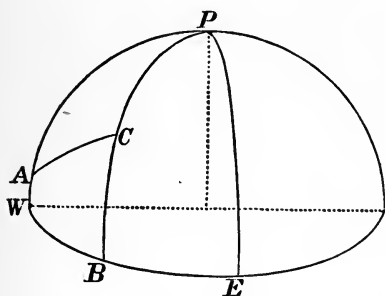
*Ans.* Course =  $N. 47^{\circ} 6\frac{1}{2}' E.$ ; dist. = 1774.9 miles.

## CHAPTER II

## GREAT CIRCLE SAILING

**26.** *To find the distance on the arc of a great circle between two points on the earth, the latitude and longitude of each point being given.*

Suppose  $A$  and  $C$  to represent the two points. If  $P$  represents the pole of the earth,  $WE$  a part of the



equator,  $PE$  the meridian from which longitude is reckoned, and  $PW$  and  $PB$  meridians through  $A$  and  $C$ , then,  $WB$  will be the difference of longitude between  $A$  and  $C$ ;  $WA$  will measure the

latitude of  $A$ , and  $BC$  will measure the latitude of  $C$ .

In the spherical triangle  $APC$ ,

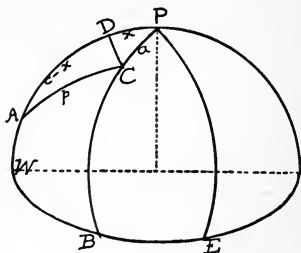
$$AP = PW - AW = 90^\circ - \text{lat. of } A;$$

$$PC = PB - BC = 90^\circ - \text{lat. of } C;$$

angle  $APC$  is measured by arc  $WB$ , or, degrees of  $APC =$  degrees of difference of longitude; therefore, we have given two sides and included angle of a spherical triangle to find the third side.

27. If it is required to find the distance only, we may proceed in the following manner:

Denote the sides opposite  $A$ ,  $P$ , and  $C$  by  $a$ ,  $p$ , and  $c$ , respectively. From  $C$  draw an arc,  $CD$ , perpendicular to  $PA$  at  $D$ . Denote the segment  $PD$  by  $x$ . Then the segment  $AD$  will be  $c - x$ , if  $D$  falls within the triangle; if  $D$  falls on  $PA$  produced,  $AD$  will be  $x - c$ .



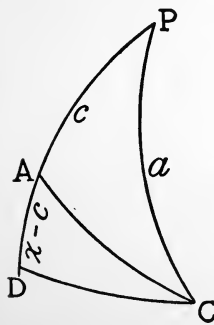
(1) Take the case where the perpendicular falls within the triangle. Applying Napier's Rule of the Circular Parts to triangle  $CDP$ , we find

$$\tan x = \frac{\cos P}{\cot a}; \tag{a}$$

also, 
$$\cos CD = \frac{\cos a}{\cos x} \tag{b}$$

In the triangle  $CDA$ , from Napier's Rule,

$$\begin{aligned} \cos p &= \cos AD \cos CD \\ &= \frac{\cos (c - x) \cos a}{\cos x}. \end{aligned} \tag{c}$$



(2) If the perpendicular falls without the triangle, then  $PD = x$ , and equations for  $\tan x$  and  $\cos CD$  remain the same; but for  $\cos AD$  we have  $\cos (x - c)$ , so that the equation for  $P$  becomes

$$\cos p = \frac{\cos(x - c) \cos a}{\cos x} \quad (d)$$

To find  $p$ , therefore, it is necessary only to compute  $x$  from equation (a), and to substitute its value in (c) or (d).

Ex. 1. It is required to find the distance, on the arc of a great circle, between a point in lat.  $40^{\circ} 28' N.$ , long.  $74^{\circ} 8' W.$ , and a point in lat.  $55^{\circ} 18' N.$ , long.  $6^{\circ} 24' W.$  Let the first point be represented by  $A$  and the second point by  $C$  in a figure similar to the first figure of the preceding article.

$$\text{Then,} \quad c = PA = 90^{\circ} - 40^{\circ} 28' = 49^{\circ} 32',$$

$$a = PC = 90^{\circ} - 55^{\circ} 18' = 34^{\circ} 42',$$

$$\text{angle } APC = P = WB = 74^{\circ} 8' - 6^{\circ} 24' = 67^{\circ} 44'.$$

$$\tan x = \frac{\cos 67^{\circ} 44'}{\cot 34^{\circ} 42'} \quad \log = 9.57855$$

$$\log \tan 14^{\circ} 42' 7'' = 9.41893$$

$$c = 49^{\circ} 32'$$

$$x = 14^{\circ} 42' 7''$$

$$c - x = 34^{\circ} 49' 53''$$

$$\cos p = \frac{\cos 34^{\circ} 49' 53'' \cos 34^{\circ} 42'}{\cos 14^{\circ} 42' 7''}$$

$$= \cos 34^{\circ} 49' 53'' \cos 34^{\circ} 42' \sec 14^{\circ} 42' 7''.$$

$$\log \cos 34^{\circ} 49' 53'' = 9.91425$$

$$\log \cos 34^{\circ} 42' = 9.91495$$

$$\log \sec 14^{\circ} 42' 7'' = 10.01445$$

$$\log \cos 45^{\circ} 45' 37'' = 9.84365$$

$$p = 45^{\circ} 45' \frac{37}{10} = 2745.6 \text{ nautical miles.}$$



Ex. 2. It is required to find the distance, on the arc of a great circle, between a point in lat.  $32^{\circ} 44'$  N., long.  $73^{\circ} 26'$  W., and a point in lat.  $8^{\circ} 14'$  S., long.  $14^{\circ}$  W.

$$c = 90^{\circ} - 32^{\circ} 44' = 57^{\circ} 16',$$

$$a = 90^{\circ} + 8^{\circ} 14' = 98^{\circ} 14',$$

$$P = 73^{\circ} 26' - 14^{\circ} = 59^{\circ} 26'.$$

$$\tan PD = \tan x = \frac{\cos 59^{\circ} 26'}{\cot 98^{\circ} 14'}$$

$$\log = 9.16046$$

$$\log = 9.70633$$

$$\log \tan 105^{\circ} 52' 57\frac{1}{2}'' = 10.54587$$

$\tan x =$  minus quantity.

$\therefore x$  or  $PD$  is  $> 90^{\circ}$ .

$$x = 105^{\circ} 52' 57\frac{1}{2}''$$

$$c = 57^{\circ} 16'$$

$$x - c = 48^{\circ} 36' 57\frac{1}{2}''$$

$$\cos AC = \cos p = \frac{\cos 48^{\circ} 36' 57\frac{1}{2}'' \cos 98^{\circ} 14'}{\cos 105^{\circ} 52' 57\frac{1}{2}''}$$

$$\log \cos 48^{\circ} 36' 57\frac{1}{2}'' = 9.82027$$

$$\log \cos 98^{\circ} 14' = 9.15596$$

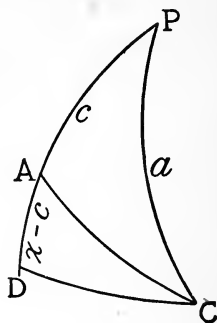
$$\log \sec 105^{\circ} 52' 57\frac{1}{2}'' = 10.56278$$

$$\log \cos 69^{\circ} 45' 37'' = 9.53901$$

$$p = 69^{\circ} 45\frac{3}{6}' = 4185.6 \text{ nautical miles.}$$

Ex. 3. Required to find the distance, on the arc of a great circle, between a point in lat.  $41^{\circ} 4'$  N., long.  $69^{\circ} 55'$  W., and a point in lat.  $51^{\circ} 26'$  N., long.  $9^{\circ} 29'$  W. *Ans.* 2507.5 miles.

Ex. 4. Required to find the distance, on the arc of a great circle, between a point in lat.  $37^{\circ} 48'$  N., long.  $122^{\circ} 28'$  W., and a point in lat.  $6^{\circ} 9'$  S.,  $8^{\circ} 11'$  E. *Ans.* 7516.3 miles.



28. When a ship sails between two points, making the shortest distance between these points, it sails on the arc of a great circle.

To do this, it cannot continue on the *same course*, as an arc of a great circle between two points, of different latitudes and longitudes, does not cut the meridians at the same angle.

Thus taking Ex. 1 of the previous article and solving by Napier's Analogies, we have:

$$\frac{c+a}{2} = \frac{155^{\circ} 30'}{2} = 77^{\circ} 45'; \quad \frac{P}{2} = 29^{\circ} 43'.$$

$$\frac{c-a}{2} = \frac{40^{\circ} 58'}{2} = 20^{\circ} 29';$$

$$\tan \frac{1}{2}(C+A) = \cos 20^{\circ} 29' \times \cot 29^{\circ} 43' \sec 77^{\circ} 45',$$

$$\text{and } \tan \frac{1}{2}(C-A) = \sin 20^{\circ} 29' \cot 29^{\circ} 43' \operatorname{cosec} 77^{\circ} 45'.$$

log cos 20° 29' = 9.97163	log sin 20° 29' = 9.54399
log cot 29° 43' = 10.24353	log cot 29° 43' = 10.24353
log sec 77° 45' = 10.67330	log cosec 77° 45' = 10.01000
log tan 82° 38' = 10.88846	log tan 32° 6' 10" = 9.79752

$$\frac{1}{2}(C+A) = 82^{\circ} 38'$$

$$\frac{1}{2}(C-A) = 32^{\circ} 6' 10''$$

$$A = 50^{\circ} 31' 50''$$

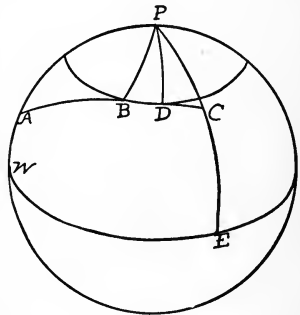
$$C = 114^{\circ} 44' 10''$$

We see, therefore, that the distance  $AC$  makes an angle with the meridian  $PA$  of  $50^{\circ} 31' 50''$ , and with the meridian  $PC$ , of  $114^{\circ} 44' 10''$ . Consequently, the vessel starts on a course N.  $50^{\circ} 31' 50''$  E., and ends with a course N.  $65^{\circ} 15' 50''$  E. (the supplement of  $114^{\circ} 44' 10''$ ). Between the points  $A$  and  $C$  the course would be continually changing. In practice, the course is altered at certain intervals, as, for instance, at points

$10^\circ$  in longitude apart, for which the new course is calculated, and the distance between the points is run by Mercator's Sailing.

29. In great circle sailing, the arc of the circle might lead to too high a latitude, or to some obstacle like land or ice, which it would be necessary to avoid. In such cases *composite sailing* is adopted, or a combination of sailing on the arcs of great circles and on a parallel of latitude.

Thus, suppose it were desired to sail from  $A$  to  $C$  by composite sailing, and that  $BD$  were the parallel of highest latitude to be reached. The great circle starting from  $A$  and tangent to the parallel is first found; then the great circle through  $C$  and tangent to  $BD$  at  $D$  is found.



Since these circles are tangent to  $BD$ ,  $AB$  is perpendicular to the meridian  $PB$ ,\* and  $CD$  is perpendicular to the meridian  $PD$ .

We have, therefore, two right-angled spherical triangles,  $APB$  and  $CDP$ , in each of which an hypotenuse and a side are given;  $PA$  from the latitude of  $A$  and  $PC$  from the latitude of  $C$  are known;  $PB$  and  $PD$ , since each is the complement of the latitude of the highest parallel to be reached, are also known. Conse-

\*  $PB$  is the least line which can be drawn from  $P$  to arc  $AB$ , and therefore passes through the pole of  $AB$ . Consequently, by geometry,  $PB$  cuts  $AB$  at right angles.

quently, the other parts of these triangles can be computed by Napier's Rule of the Circular Parts. We can thus ascertain the courses at  $A$  and  $C$  and the angles  $APB$  and  $DPC$ . The angles  $APB$  and  $DPC$  will give us the difference of longitude between  $A$  and  $B$ , and between  $C$  and  $D$ . Since the longitudes of  $A$  and  $C$  are known, the longitudes of  $B$  and  $D$  are also known. By this method of sailing the vessel goes on the arc of a great circle from  $A$  to  $B$ , on a parallel of latitude from  $B$  to  $D$  (in the figure due E.), and then on a great circle from  $D$  to  $C$ .

Ex. 1. A ship sails on a composite track from lat.  $37^{\circ} 15' N.$ , long.  $75^{\circ} 10' W.$  to lat.  $48^{\circ} 23' N.$ , long.  $4^{\circ} 30' W.$ , not going north of lat.  $49^{\circ} N.$  Required, the longitude of the point of arrival on the parallel of  $49^{\circ} N.$ , the longitude of the point of departure from the parallel, the initial and final courses, and the total distance sailed.

In the triangle  $ABP$  right-angled at  $B$ ,  $PA = 52^{\circ} 45'$ ,  $PB = 41^{\circ}$ .

In the triangle  $PDC$  right-angled at  $D$ ,  $PC = 41^{\circ} 37'$ ,  $PD = 41^{\circ}$ .

$$\cos APB = \cot 52^{\circ} 45' \tan 41^{\circ}$$

$$\cos DPC = \cot 41^{\circ} 37' \tan 41^{\circ}$$

$$\log \cot 52^{\circ} 45' = 9.88105$$

$$\log \cot 41^{\circ} 37' = 10.05141$$

$$\log \tan 41^{\circ} = 9.93916$$

$$\log \tan 41^{\circ} = 9.93916$$

$$\log \cos 48^{\circ} 37' 21'' = 9.82021$$

$$\log \cos 11^{\circ} 53' 40'' = 9.99057$$

$$\sin A = \frac{\sin 41^{\circ}}{\sin 52^{\circ} 45'} \quad \log = 9.81694$$

$$\log \sin 55^{\circ} 30' 27'' = 9.91603$$

$$\sin C = \frac{\sin 41^{\circ}}{\sin 41^{\circ} 37'} \quad \log = 9.81694$$

$$\log \sin 81^{\circ} 3' = 9.99468$$

$$\cos AB = \frac{\cos 52^\circ 45'}{\cos 41^\circ} \quad \log = 9.78197$$

$$\log = 9.87778$$

$$\log \cos 36^\circ 40' 33'' = 9.90419$$

$$\cos CD = \frac{\cos 41^\circ 37'}{\cos 41^\circ} \quad \log = 9.87367$$

$$\log = 9.87778$$

$$\log \cos 7^\circ 52' = 9.99589$$

$$\text{long. of } A = 75^\circ 10' \text{ W.}$$

$$\text{dif. of long.} = 48^\circ 37'.4 \text{ E.}$$

$$\text{long. of } B = 26^\circ 32'.6 \text{ W.}$$

$$\text{long. of } C = 4^\circ 30' \text{ W.}$$

$$\text{dif. of long.} = 11^\circ 53'\frac{2}{3} \text{ W.}$$

$$\text{long. of } D = 16^\circ 23'.7 \text{ W.}$$

$$\text{Course at } A = \text{N. } 55^\circ 30' 27'' \text{ E.}$$

$$\text{Course at } C = \text{S. } 81^\circ 3' \text{ E.}$$

$$\text{long. of } B = 26^\circ 32'.6 \text{ W.}$$

$$\text{long. of } D = 16^\circ 23'.7 \text{ W.}$$

$$\text{dif. of long.} = 10^\circ 8'.9 \text{ W.}$$

$$\text{dist. } AB = 2200.55$$

$$\text{dist. } BD = 399.5$$

$$\text{dist. } CD = 472.0$$

$$= 608.9 \quad \log = 2.78455 \quad \text{total dist.} = 3072.05 \text{ miles}$$

$$\log \cos 49^\circ = 9.81694$$

$$\log 399.5 = 2.60149$$

Ex. 2. A vessel sails on a composite track from a point in lat.  $46^\circ 10' \text{ S.}$ , long.  $45^\circ \text{ E.}$  to a point in lat.  $43^\circ 40' \text{ S.}$ , long.  $71^\circ 15' \text{ W.}$ , not going S. of parallel of  $50^\circ \text{ S.}$  Required the longitude of the point of arrival on the parallel of  $50^\circ \text{ S.}$ , the longitude of the point of departure from that parallel, the initial and final courses, and the total distance sailed.

Ans.  $15^\circ 55'.4 \text{ E.}$ ,  $34^\circ 27'.9 \text{ W.}$ ; S.  $68^\circ 8' 48'' \text{ W.}$ ; N.  $62^\circ 42' \text{ W.}$ ; 4663.2 miles.

## CHAPTER III

## COURSES

THE magnetic needle of the compass is supposed to give a north and south line, but in point of fact it rarely points north and south. It is subject to influences which deflect it from a north and south line; so that the north point of the magnet is sometimes east and sometimes west of a true north and south line. The most important deflecting influences cause two errors, as they are called; namely, an error of *Variation*, and an error of *Deviation*.

The error of *Variation* is due to the magnetic action of the earth. The error is greater or less, or even nothing, according to the position of the compass at various points on the earth's surface. Variation may therefore be called a geographical error. It is known and calculable, and allowance can be made for it at any point on the earth.

The error of *Deviation* is due to the magnetic action of the ship and its cargo, and changes according to the direction in which the ship is headed. Each ship has its own error of Deviation. This error can be known, and, to a certain extent, can be counteracted by proper arrangements, but must always be taken into account.

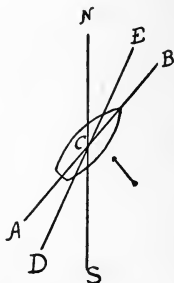
**30.** The *True Course* of a ship is the angle between the distance, or the line traversed by the ship, and the meridian or true north and south line.

**31.** The *Magnetic Course* of a ship is the angle between the distance and a north and south line, as indicated by the *magnet of a compass which is not affected by the error of Deviation*.

**32.** The *Compass Course* of a ship is the angle between the distance and a north and south line, as indicated by the *compass of a ship*.

**33.** For a steamship, in calm weather, or in a sailing vessel with a wind directly astern, the *Compass Course*, when corrected for variation and deviation, will give the *True Course*; but when the wind blows from any direction, except from right ahead or astern, it pushes the vessel aside from the course on which she is headed, so that her track is not in the direction in which she is headed, but makes an angle with that direction. This angle is called *leeway*, because the push of the wind on the vessel is to *leeward*.

Thus, in the figure  $NS$  is a true meridian;  $NCB$  is the *apparent course*;  $NCE$  is the *true course*; the wind, shown by the direction of the arrow, diverting the vessel from the track  $AB$ , in which she is headed, to the true track  $DE$ . The *angle between these tracks,  $ECB$ , leeway*; is given in points; and is estimated by the eye.



Although leeway is not an error of the compass, the effect of it is the same as if it were, and allowance must be made for it in order to determine the true course of a ship.

In navigation it is important to be able to convert a true course into a compass course and also a compass course into a true course, by applying corrections for the various errors, which have been mentioned.

The method of doing this will be best ascertained by applying the errors one by one.

In expressing, or converting courses, the observer is supposed to be at the *center* of the compass card.

**34.** To convert a *true course into a magnetic course*, the *variation* being given.\*

Both variation and deviation are given in terms which are applied to the *north* point of the compass needle. For instance, if the variation is given as  $8^{\circ}$  E., the *north* point of the needle points  $8^{\circ}$  east of a true N. and S. line, or, looking from the center of the compass,  $8^{\circ}$  to the *right* of that line.

Looking *south* from the center, the variation would still be  $8^{\circ}$  to the *right*.

In works on Navigation it is customary to give rules for converting courses, but it is best to draw a diagram, which will illustrate the example given, and after a little practice, rules can be derived by the learner himself.

\* Variation charts are published by the Government Coast Survey.



Ex. 1. Let the true course be N.E. b. N. and the variation be  $8^\circ$  E. Required the magnetic course.

Suppose the observer to be at  $O$ ; the line  $NS$  = true N. and S. line;  $N_m S_m$  = magnetic N. and S. line.

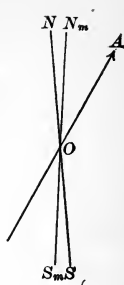
true course =  $NOA = 33^\circ 45'$  to right of N.

variation =  $NON_m = 8^\circ$  to right of N.

---

mag. course =  $N_m OA = 25^\circ 45'$  to right of N.

or N.N.E.  $\frac{1}{4}$  E., nearly.



Ex. 2. Let the true course be N.W., and the variation be  $12^\circ$  W.

$NS$  = true N. and S. line;  $N_m S_m$  = magnetic N. and S. line.

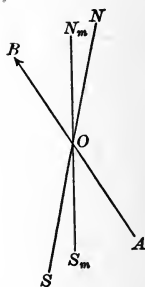
true course =  $BON = 45^\circ$ , or 4 pts. left of N.

variation =  $N_m ON = 12^\circ$ , or 1 pt., nearly, left of N.

---

mag. course =  $N_m OB = 33^\circ$ ,

or 3 pts. left of N. = N.W. b. N.



In converting courses sometimes the work is expressed in degrees, and sometimes to the nearest points, half points, or quarter points.

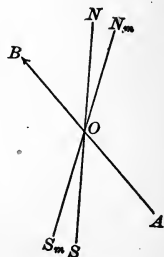
Ex. 3. If the course is N.W., and the variation is  $12^\circ$  E., to obtain the magnetic course we *add* the  $12^\circ$  to the true course.

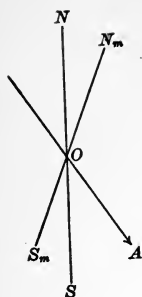
true course =  $NOB = 45^\circ$ , or 4 pts. left of N.

variation =  $NON_m = 12^\circ$ , or 1 pt. right of N.

---

mag. course =  $N_m OB = 57^\circ$ , or 5 pts. left of N.





Ex. 4. Let true course be S.E. b. S. and variation be  $22^\circ$  E.

$NS$  = true N. and S. line.

$N_m S_m$  = magnetic N. and S. line.

Suppose observer to be at  $O$ .

true course  $SOA = 3$  pts. left of S.

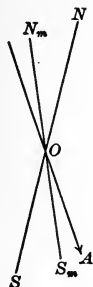
=  $33^\circ 45'$  left of S.

variation  $SOS_m = 22^\circ$  right of S.

---

magnetic course =  $S_m OA = 55^\circ 45'$  left of S.

= nearly 5 pts. left of S.



Ex. 5. Let true course be S.E. b. S., but variation be  $22^\circ$  W.

true course  $SOA = 33^\circ 45'$  left of S.

variation  $SOS_m = 22^\circ$  left of S.

---

magnetic course =  $S_m OA = 11^\circ 45'$  left of S.

From these examples and by an inspection of the figures, supposing the observer to be at center of compass, it will be seen that *when the true course and the variation are both to the right or both to the left of either the N. or S. points, the magnetic course is the difference of the two; but when one is to the right and the other to the left of the N. or S. points, the magnetic course is the sum of the two.*

**35.** To change a *magnetic course* into a *true course*: if the given course and variation are *both to the right or both to the left of either N. or S. points*, add the two; if *one is to the right and the other to the left*, take the *difference*.

This rule for changing magnetic to true courses would naturally follow, from what has been said of converting true courses into magnetic courses, as the processes are reversed, and we should, therefore, reverse the former rule. We will illustrate by examples.

Ex. 1. Magnetic course is N.N.E. Variation is  $22^{\circ}$  E. Find true course.

$$\text{mag. course} = N_m AB = 22^{\circ} 30' \text{ right of N.}$$

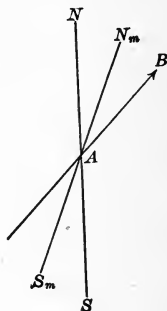
$$\text{variation} = N_m AN = 22^{\circ} \text{ right of N.}$$

---


$$\text{true course} = NAB = 44^{\circ} 30' \text{ right of N.}$$

$$= 4 \text{ pts., nearly.}$$

$$= \text{N.E., nearly.}$$



Ex. 2. Let the magnetic course be S.E. b. S., and the variation be  $11^{\circ}$  W. Find true course.

$$\text{mag. course} = S_m AB = 33^{\circ} 45' \text{ left of S.}$$

$$\text{variation} = S_m AS = 11^{\circ} \text{ left of S.}$$

---


$$\text{true course} = SAB = 44^{\circ} 45' \text{ left of S.}$$

$$= \text{S.E., nearly.}$$



Ex. 3. Let the magnetic course be S.W. b. W., and the variation be  $11^{\circ} 15'$  W. Find true course.

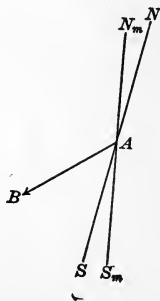
$$\text{mag. course} = S_m AB = 5 \text{ pts. right of S.}$$

$$\text{variation} = S_m AS = 1 \text{ pt. left of S.}$$

---


$$\text{true course} = SAB = 4 \text{ pts. right of S.}$$

$$= \text{S.W.}$$



36. To convert magnetic courses into compass courses, or compass courses into magnetic courses, it is necessary to have a list of deviations corresponding to the different directions in which the ship heads. This is determined before the ship leaves port. Deviation acting on the compass needle to deflect it from a *magnetic* N. and S. line, tables of deviation give the amounts of deviation E. and W. of the magnetic north point.

Though each ship has its own Deviation Table, the table here given will serve to illustrate the subject.

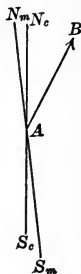
DEVIATION TABLE

I. Direction in Degrees and Minutes.	I. Course by Ship's Compass.	II. Deviation of the Compass.	I. Course by Ship's Compass.	II. Deviation of the Compass.
0	North	3° 10' W.	South	3° 10' E.
11° 15'	N. b. E.	2 35 E.	S. b. W.	0 5 E.
22 30	N.N.E.	8 10 E.	S.S.W.	3 0 W.
33 45	N.E. b. N.	13 10 E.	S.W. b. S.	6 30 W.
45	N.E.	16 50 E.	S.W.	9 40 W.
56 15	N.E. b. E.	19 30 E.	S.W. b. W.	13 0 W.
67 30	E.N.E.	20 30 E.	W.S.W.	16 10 W.
78 45	E. b. N.	21 5 E.	W. b. S.	19 15 W.
90	East	20 20 E.	West	21 10 W.
78 45	E. b. S.	19 15 E.	W. b. N.	23 20 W.
67 30	E.S.E.	18 5 E.	W.N.W.	24 0 W.
56 15	S.E. b. E.	16 30 E.	N.W. b. W.	23 35 W.
45	S.E.	14 40 E.	N.W.	22 0 W.
33 45	S.E. b. S.	12 5 E.	N.W. b. N.	19 0 W.
22 30	S.S.E.	9 40 E.	N.N.W.	14 50 W.
11 15	S. b. E.	6 0 E.	N. b. W.	9 15 W.
	South	3 10 E.	North	3 10 W.

**37.** To find the *magnetic course*, having given the *compass course* and the *deviation*.

Ex. 1. Let the compass course be N.N.E. By the table the deviation is  $8^{\circ} 10'$  E.

Let  $N_m S_m$  be magnetic N. and S. line;  $N_c S_c$  be compass N. and S. line; and  $AB$  be ship's track.



$$\text{com. course} = N_c AB = 22^{\circ} 30' \text{ right of N.}$$

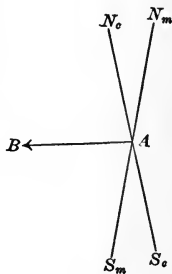
$$\text{deviation} = N_c AN_m = 8^{\circ} 10' \text{ right of N.}$$

---


$$\text{mag. course} = N_m AB = 30^{\circ} 40' \text{ right of N.}$$

$$= \text{N.N.E. } \frac{3}{4} \text{ E.}$$

Ex. 2. Let the compass course be N.  $80^{\circ}$  W. This is  $1\frac{1}{4}^{\circ}$  W. of W. b. N. The deviation for W. b. N. is  $23^{\circ} 20'$  W. The deviation for N.  $80^{\circ}$  W. will be a little less. As in steering a vessel it is impossible to hold her head to a minute of correction, if we call the deviation  $23^{\circ}$  W. we shall not be much out of the way.



$$\text{com. course} = N_c AB = 80^{\circ} \text{ left of N.}$$

$$\text{deviation} = N_c AN_m = 23^{\circ} \text{ left of N.}$$

---


$$\text{mag. course} = N_m AB = 103^{\circ} \text{ left of N.}$$

$$= 77^{\circ} \text{ right of S.}$$

$$\text{mag. course} = \text{S. } 77^{\circ} \text{ W.}$$

**38.** To find the *compass course*, the *magnetic course* and *deviation* being given.

Ex. 1. Let the magnetic course be E.N.E.

$$\text{magnetic course} = 6 \text{ pts. right of N. or N. } 67^{\circ} 30' \text{ E.}$$

$$\text{deviation from page 56} = 1\frac{3}{4} \text{ pts. right of N. or N. } 20^{\circ} 30' \text{ E.}$$

---


$$\text{approximate compass course} = 4\frac{1}{4} \text{ pts. right of N. or N. } 47^{\circ} \text{ E.}$$

This is only an approximate answer, as will be evident; for if we steer by *compass* N. 47° E., the deviation for that course is nearly 17° 30'. Thus:

$$\begin{aligned} \text{compass course} &= 47^\circ \text{ right of N.} \\ \text{deviation} &= 17^\circ 30' \text{ right of N.} \end{aligned}$$

---


$$\begin{aligned} \text{magnetic course would then} &= 64\frac{1}{4}^\circ \text{ right of N.} \\ &\text{or } 3\frac{1}{4}^\circ \text{ less than the given course.} \end{aligned}$$

But, if we apply to the given magnetic course the correction due to deviation for the *approximate* compass course, the example will prove. Thus:

$$\begin{aligned} \text{magnetic course} &= 6 \text{ pts. or } 67^\circ 30' \text{ right of N.} \\ \text{deviation for N. } 4\frac{1}{4} \text{ E.} &= 1\frac{1}{2} \text{ pts. or } 17^\circ 30' \text{ right of N.} \end{aligned}$$

---


$$\text{compass course N.E. } \frac{1}{2} \text{ E.} = 4\frac{1}{2} \text{ pts. or } 50^\circ \text{ right of N.}$$

$$\begin{aligned} \text{Proof: compass course} &= 4\frac{1}{2} \text{ pts. or } 50^\circ \text{ right of N.} \\ \text{deviation} &= 1\frac{1}{2} \text{ pts. or } 17^\circ 30' \text{ right of N.} \end{aligned}$$

---


$$\text{magnetic course} = 6 \text{ pts. or } 67^\circ 30' \text{ right of N.}$$

Courses and deviations, when given in points, are given to *nearest* points, half points, or quarter points.

Since the Deviation tables are made for angles indicated by the compass courses, we get only an *approximate* result by applying the deviation corresponding to the *magnetic course*. Hence, to be accurate, we first find this approximate compass course, and then apply the correction, which corresponds to this approximate course in the table, to the original magnetic course.

We have considered the applications of variation and deviation separately, for the sake of clearness; but in practice, their action on the magnet of the

compass is combined. We have to convert compass courses into true courses, and also true courses into compass courses.

In changing a compass course into a true course the result is the same, whether we apply corrections for variation and deviation separately, or together; but *in converting a true course into a compass course we must apply correction for variation first, and then correction for deviation.*

Ex. 1. Find *true course*; variation being  $25^\circ$  E.; compass course being N.N.E.; and deviation being taken from table on page 56. In figure let notation of lines be the same as in preceding figures.

compass course =  $N_c AB = 22^\circ 30'$  right of N.

variation =  $NAN_m = 25^\circ$  right of N.

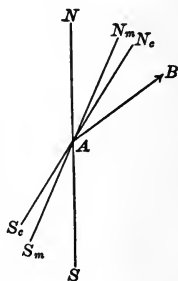
deviation =  $N_m AN_c = 8^\circ 10'$  right of N.

sum =  $NAN_c = 33^\circ 10'$  right of N.

---

true course =  $NAB = 55^\circ 40'$  right of N.

= nearly N.E. b. E.



Ex. 2. Find true course, variation being  $25^\circ$  W.; compass course being S.E. b. E.; and deviation being taken from table.

variation =  $NAN_m$

=  $SAS_m = 2\frac{1}{4}$  pts. left of S.

deviation =  $S_c AS_m = 1\frac{1}{2}$  pts. right of S.

---

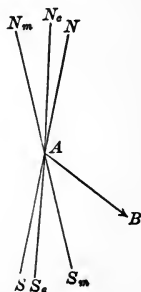
difference =  $SAS_c = \frac{3}{4}$  pt. left of S.

compass course =  $S_c AB = 5$  pts. left of S.

---

true course =  $SAB = 5\frac{3}{4}$  pts. left of S.

= E.S.E.  $\frac{1}{4}$  S.



Ex. 3. Let the true course be N. 35° W. and the variation be 10° E. Find the compass course.

$$\text{true course} = NAB = 35^\circ \text{ left of N.}$$

$$\text{variation} = NAN_m = 10^\circ \text{ right of N.}$$

$$\text{magnetic course} = N_mAB = 45^\circ \text{ left of N.}$$

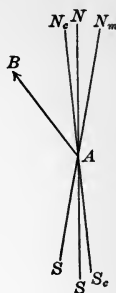
$$\text{deviation (approximate)} = 22^\circ \text{ left of N.}$$

$$\text{approx. compass course} = 23^\circ \text{ left of N.}$$

$$\text{deviation} = 14^\circ 50' \text{ left of N.}$$

$$\text{compass course } N_cAB = 30^\circ 10' \text{ left of N.}$$

$$= \text{N. } 30^\circ 10' \text{ W.}$$



Ex. 4. Let the true course be N.E. b. E. and the variation be 20° W. Find the compass course.

$$\text{true course} = NAB = 5 \text{ pts. right of N.}$$

$$\text{variation} = NAN_m = 1\frac{3}{4} \text{ pts. left of N.}$$

$$\text{magnetic course} = N_mAB = 6\frac{3}{4} \text{ pts. right of N.}$$

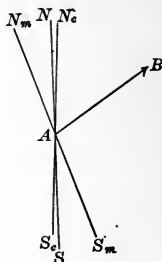
By table, page 56:

$$\text{approximate deviation} = 1\frac{3}{4} \text{ pts. right of N.}$$

$$\text{approx. compass course} = 5 \text{ pts. right of N.}$$

$$\text{deviation} = 1\frac{3}{4} \text{ pts. right of N.}$$

$$\text{compass course} = 5 \text{ pts. right of N.}$$



Same examples by degrees:

$$\text{true course} = NAB = 56^\circ 15' \text{ right of N.}$$

$$\text{variation} = NAN_m = 20^\circ \text{ left of N.}$$

$$\text{magnetic course} = N_mAB = 76^\circ 15' \text{ right of N.}$$

$$\text{approximate deviation} = 21^\circ \text{ right of N.}$$

$$\text{approximate compass course} = 55^\circ 15' \text{ right of N.}$$

$$\text{deviation (to be taken from } 76^\circ 15') = 19^\circ 30' \text{ right of N.}$$

$$\text{compass course} = N_cAB = 56^\circ 45' \text{ right of N.}$$

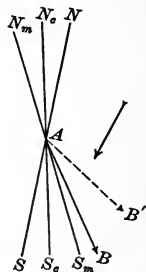


Ex. 5. Find the true course; the compass course being S.E., the variation being  $28^\circ$  W., leeway being 2 pts., and the wind blowing E.N.E. Take deviation from table on page 56.

$$\begin{aligned} \text{compass course} &= S_c AB' = 45^\circ \text{ left of S.} \\ \text{deviation} &= S_c AS_m = 14^\circ 40' \text{ right of S.} \\ \text{variation} &= S_m AS = 28^\circ \text{ left of S.} \\ \hline \text{dif.} &= S_c AS = 13^\circ 20' \text{ left of S.} \end{aligned}$$

$$\text{appar. true course} = SAB' = 58^\circ 20' \text{ left of S.}$$

But the influence of the wind, whose direction is shown by arrow in figure, changes this apparent true course to the leeward by two points, represented by the angle  $BAB'$ .



Thus:

$$\begin{aligned} \text{apparent true course} &= SAB' = 58^\circ 20' \text{ left of S.} \\ \text{leeway} &= BAB' = 22^\circ 30' \text{ toward S., or right of S.} \\ \hline \text{true course} &= SAB = 35^\circ 50' \text{ left of S., or S.E. } \frac{3}{4} \text{ S.} \end{aligned}$$

Ex. 6. Compass course is S.W.  $\frac{1}{4}$  S. Variation is  $6^\circ$  E.; wind is S.S.E., and leeway  $1\frac{3}{4}$  pts. Deviation being taken from table on page 56. Find true course. Example can be worked without figure thus:

$$\begin{aligned} \text{course by compass} &= 3\frac{3}{4} \text{ pts. right of S.} \\ \text{variation} &= 6^\circ \text{ right of S.} \\ \text{deviation} &= 9^\circ \text{ left of S.} \\ \hline \text{dif.} &= 3^\circ \text{ left of S.} = \frac{1}{4} \text{ pt. left of S.} \\ \hline \text{apparent true course} &= 3\frac{1}{2} \text{ pts. right of S.} \\ \text{leeway} &= 1\frac{3}{4} \text{ pts. right of S.} \\ \hline \text{true course} &= 5\frac{1}{4} \text{ pts. right of S.} \\ &= \text{W.S.W. } \frac{3}{4} \text{ S.} \end{aligned}$$

The preceding examples could all have been worked without figures, but, until the learner has become familiar with the methods of applying the different corrections, it is best to check the numerical work by means of a diagram.

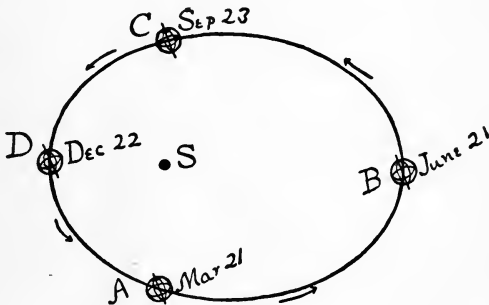
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## CHAPTER IV

## ASTRONOMICAL TERMS

39. Before giving definitions of the terms used in Nautical Astronomy, we must first consider the effects of the earth's revolution around the sun, as they appear to an observer on the earth.

In the figure, let  $ABCD$  represent the orbit in which the earth revolves about the sun,  $S$ ; and

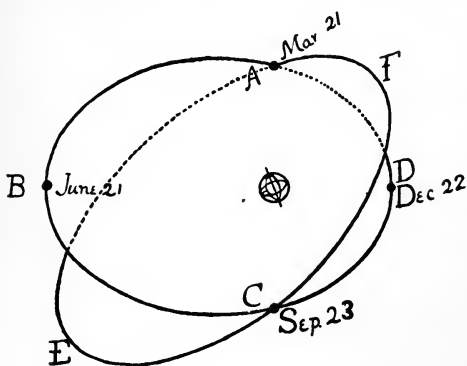


$A$ ,  $B$ ,  $C$ , and  $D$  represent the positions of the earth at the beginning of the seasons of spring, summer, fall, and winter, respectively. If the figure represents the plane of the earth's orbit, the axis of the earth is not at right angles to that orbit, but makes an angle with it of about  $66^{\circ} 33'$ . The plane of the equator therefore makes an angle with it of  $23^{\circ} 27'$ .

To the observer on the earth the heavenly bodies, the sun included, appear to be on the interior surface of a very large sphere, of which the center is his own point of observation, or his own eye. This imaginary interior surface of a *sphere* is called the *celestial concave*. The poles of the heavens are the points of the celestial concave, toward which the axis of the earth is directed. The celestial pole *above* the horizon is called the *elevated* pole.

Considering the earth as motionless, to the observer on it, the *sun* appears to travel daily in the celestial concave from east to west. If from a standpoint on the earth we could watch the sun in the heavens during the whole year, it would appear to describe a circle on the celestial concave. This circle is called the *ecliptic*.

The plane of the earth's equator, being supposed produced, would cut the celestial concave in the



celestial equator or *equinoctial*.

The ecliptic and the equinoctial intersect in two

points, known as the first point of

Aries and the first point of Libra.

About March 21

the center of the

sun is at the first point of Aries, where the equinoct-

tial crosses the ecliptic: and about September 23 it is at the first point of Libra, where the equinoctial intersects the ecliptic a second time. These points of intersection are called equinoctial points, because, at the seasons of the year when the sun reaches them, the days and nights are of nearly equal length. Thus in the figure,  $ABCD$  is the ecliptic.  $AECF$  is the equinoctial.  $A$  is the first point of Aries, where the sun changes its declination from S. to N.;  $C$  is the first point of Libra, where the sun changes its declination from N. to S.

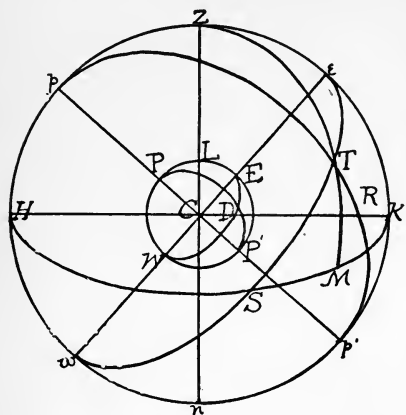
The equinoctial is a fixed circle on the celestial concave, and the first point of Aries is considered a fixed point,\* as it is the point of intersection of the ecliptic and the equinoctial. The positions of heavenly bodies may therefore be expressed with reference to them, just as the positions of places on the earth's surface are expressed in latitude and longitude by reference to the equator and the meridian of Greenwich.

40. Let the accompanying figure represent the earth,  $PWP'E$ , surrounded by the celestial sphere,  $ppp'e$ .

If the axis of the earth,  $PP'$ , be produced to meet the celestial concave in the points  $p$  and  $p'$ , these points are called the *celestial poles*, and the line  $pp'$  is called the *axis* of the celestial sphere.

\* First point of Aries moves yearly 50'' (nearly) to westward.

The plane of the equator,  $WDE$ , produced, intersects the celestial sphere in the *celestial equator*,  $wSe$ .



The planes of the meridians  $PEP'$ ,  $PDP'$ , intersect the celestial sphere in great circles,  $pep'$ ,  $pTp'$ , which are called *hour circles* and also circles of declination.

Since the earth revolves upon its axis once in 24 hours, every point on a ce-

lestial meridian would appear, to an observer on the earth's surface, to move through a complete circumference; or  $360^\circ$ , during that time. If, now, the celestial meridians are drawn at intervals of  $15^\circ$  (on the equator), there will be 24 such meridians. Since the time in which *all* these meridians pass by an observer is 24 hours, the interval of time of passage between two successive meridians will be one hour, since 24 of them pass by him in 24 hours. If meridians are drawn at intervals of  $1^\circ$ , the interval of time of passage of two such meridians will be  $\frac{60 \text{ minutes}}{15}$ , or 4 minutes. Thus, the passage of these meridians or of points on them being measured by time or degrees, we can convert one measure into the other.

The angles made by these meridians at  $p$  and  $p'$  are called hour angles, and these angles are measured by the arcs which they intercept on the arc of the celestial equator  $wSe$ .

The *celestial horizon* of any place, on the earth's surface, is the circle made by a plane passing through the center of the earth parallel to the plane of the horizon at that place, and intersecting the celestial sphere.

The celestial horizon of the point  $L$  is  $HSK$ .

If a straight line be drawn from the center,  $C$ , to  $L$ , and this line be produced through  $L$  to meet the celestial sphere at  $Z$ ,  $Z$  will be the zenith of  $L$ ;  $Zp$  will measure the *zenith distance* of  $L$  (i.e. the distance of the zenith of the point  $L$  from the pole), and  $Ze$  will measure the *celestial latitude* of  $L$ . The zenith distance is the complement of the celestial latitude. The *degree measure* of the *celestial latitude* is the same as that of the *terrestrial latitude*, since they both subtend the same angle at the center of the earth. Thus,  $Ze$  and  $LE$  both subtend the angle  $LCE$ .

Since  $Z$  is the extremity of the diameter perpendicular to the plane of the horizon  $HSK$ ,  $Z$  is the pole of  $HSK$ , and therefore every point on  $HSK$  is  $90^\circ$  from  $Z$ . If the line  $CZ$  be produced to meet the surface of the celestial sphere again at  $n$ ,  $n$  will be the *nadir* of the observer at  $L$ .

The *declination* of a heavenly body is the arc of

the circle of declination, intercepted between the equinoctial and the position of the body.

Declination is measured in degrees, minutes, etc., N. or S. from the equinoctial, toward the pole.

Thus in the preceding figure,  $TR$  is the declination of  $R$  and is S. declination.

The *polar distance* of a heavenly body is the distance of that body from the *elevated* pole, and is  $90^\circ \mp$  the declination: the minus sign being taken if the declination of the body is of the same name with the pole, that is, both being N. or both S.; but the plus sign being used if the declination and the pole are not of the same name, that is, one being N. and the other S.

In the preceding figure, calling  $p$  the N. pole, and considering it the elevated pole, the polar distance of  $R$  is  $90^\circ + TR$ . If  $p'$  were taken as the elevated pole,  $p'R$  would be the polar distance and would be  $90^\circ - TR$ .

The *altitude* of a heavenly body is the angle of elevation of the body above the plane of the horizon.

A distinction is made between an *observed* altitude of a body and its *true altitude*.

By an *observed altitude*, in Navigation, is generally understood the angle of elevation of a body above the *visible horizon*, as represented by the horizon line of the sea.

A *true altitude* is an observed altitude corrected, so as to represent the angle of elevation of the body above the *celestial horizon*.



*Circles of altitude* are great circles of the celestial sphere which pass through the zenith of the observer.

Circles of altitude are also called *vertical circles* because their planes are perpendicular or vertical to the plane of the horizon.

The *altitude* of a body is *measured* on the arc of a circle of altitude between the horizon circle and the position of the body. This *measure* is generally used in calculations as *the altitude*.

In the preceding figure,  $ZeK$  and  $ZTM$  are circles of altitude.  $MT$  is the altitude of  $T$ .

The *zenith distance* of a body is its distance from the zenith measured on a circle of altitude.

$ZT$  is zenith distance of  $T$  and equals  $90^\circ - MT$  or  $90^\circ -$  altitude of  $T$ .

The *celestial meridian* of any place is the circle on the celestial concave in which the plane of the terrestrial meridian of that place produced cuts the concave.

It is the circle of altitude which passes through the celestial poles.

In the preceding figure, if  $L$  be a place on the earth's surface, and the plane of the meridian  $PLEP$  be produced to cut the celestial concave in  $HpZeK$ ,  $HpZeK$  is the celestial meridian of  $L$ . It coincides with the circle of altitude through  $Z$ .

The points in which the celestial meridian cuts the horizon are the N. and S. points of the horizon.

$H$  and  $K$  are the N. and S. points of the celestial horizon of the place  $L$ , supposing  $P$  and  $P'$  to be N. and S. poles.

The prime vertical is the circle of altitude whose plane is at right angles to the plane of the celestial meridian. It intersects the horizon in the E. and W. points.

If, in the preceding figure, a plane be passed through  $Cz$  at right angles to the plane of  $HpZeK$ , the circle in which it cuts the celestial concave will be the prime vertical.

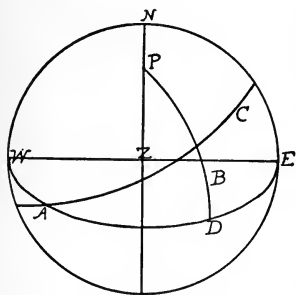
The *right ascension* of a heavenly body is the arc of the equinoctial intercepted between the first point of Aries and the circle of declination which passes through the center of the body.

Right ascension is measured eastward from the first point of Aries from  $0^\circ$  to  $360^\circ$ ; or, in hours, from 0 h. to 24 h.

Let the figure represent the celestial sphere projected on the plane of the horizon  $NWE$ ;  $P$  will represent the N. pole;

$WDE$  will represent the equinoctial;  $AC$  will represent the ecliptic; and  $A$ , the intersection of the ecliptic with the equinoctial, will represent the first point of Aries.

If  $B$  represent the position of a heavenly body, draw the arc of a circle of declination,  $PB$ , and produce the arc to meet the equinoctial at  $D$ .  $AD$  will represent the right ascension of  $B$ .



41. The earth being *inside* the celestial concave, the observer sees the heavenly bodies from the inside. Astronomical diagrams are drawn on the supposition

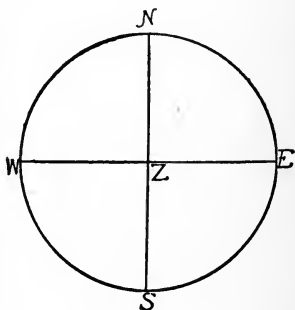
that the observer is on the *outside* of the celestial concave, as the relations and positions of celestial bodies can best be represented on this supposition. The representations are made on different planes, according to the supposed different points of view.

Thus, if the *point of view* is directly *above* the *zenith*, the representation of the heavenly bodies is made on the *plane* of the *horizon*. This is a very useful mode of representation.

If the *point of view* is at either the *E.* or *W.* points, the representation is made on the *plane* of the celestial meridian.

If the *point of view* is directly above the *celestial pole*, the representation is made on the *plane* of the *equinoctial* or *celestial equator*.

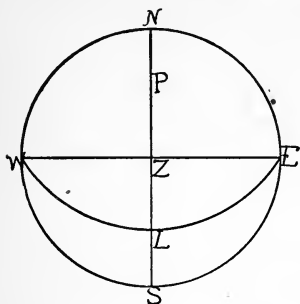
If *NWSE* represent the horizon, and if the point of view is directly above the zenith, the zenith will be projected on the center of the circle, and the *circles* of *altitude*, passing through the zenith, will be projected as straight lines. If *N*, *S*, *E*,



*W* be the *N.*, *S.*, *E.*, and *W.* points of the horizon, *NS* will be the celestial meridian of the observer whose zenith is *Z*. The *prime vertical*, or circle of altitude at right angles to the celestial meridian, in the figure will be *WE*.

42. To represent, *on the plane of the horizon*, the celestial pole and the celestial equator for a given latitude. Suppose the latitude to be  $42^\circ$  N.

Let  $ZL$  represent  $42^\circ$ , and  $LP$  represent  $90^\circ$ . If an arc of a great circle  $WLE$  be drawn with  $P$  as a pole, it will pass through  $W$ ,  $L$ , and  $E$ , and represent



the celestial equator, or equinoctial. For, since by definition, the planes of the celestial meridian and prime vertical are at right angles to each other, the diameter joining  $E$  and  $W$  lies in the plane perpendicular to the plane of  $NS$ . Therefore,  $E$

and  $W$  are poles of  $NS$ . Consequently,  $E$  and  $W$  are each at a quadrant's distance from  $P$ , for the polar distance of a great circle is a quadrant. But  $PL$  is a quadrant by construction. Therefore,  $P$  representing the celestial pole,  $WLE$  will represent the equinoctial or celestial equator.

43. The *azimuth* of a heavenly body is the angle, at the zenith of the observer, between *the celestial meridian* and the *circle of altitude passing through the body*. It is measured by an arc of the horizon between the N. and S. points and the point in which the circle of altitude intersects the horizon. Azimuth is measured from the N. and S. points E. and W. from  $0^\circ$  to  $90^\circ$ .

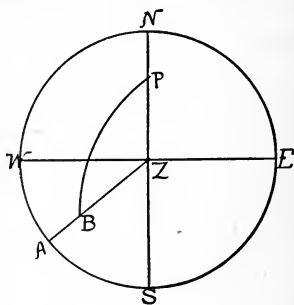
Azimuth is sometimes called the *true bearing* of a heavenly body.

To represent on the plane of the horizon *the altitude*, *zenith distance*, and *azimuth* of a heavenly body.

Let *NWSE* represent the plane of the horizon.

Let the azimuth be S.  $50^\circ$  W., and the altitude be  $30^\circ$ .

Measure  $SA = 50^\circ$ ; through *A* draw the circle of altitude, *ZA*. On *ZA* take  $AB = 30^\circ$  to represent *the altitude*. This will give *B* as the place of the heavenly body. *ZB* is the *zenith distance*. If *P* be supposed to be the celestial pole, *PB* will represent the *polar distance* of the body. *SZB* is the *azimuth*, measured by arc *SA*.



## CHAPTER V

## TIME

44. Time is measured by the intervals between the appearances of certain celestial bodies on the meridian of the observer.

Thus, *sidereal time* is measured by the successive appearances of the *first point of Aries* on the meridian. The period elapsing between two successive appearances of the first point of Aries on the same part of the meridian is called a *sidereal day*.

The *transit* of any heavenly body is its passage across the celestial meridian.

The instant when the first point of Aries, or when any heavenly body, is on the meridian is called the time of its transit.

As the celestial meridian passes through the zenith and nadir, the first point of Aries is really on the celestial meridian twice; but a *sidereal day* is measured by the *interval* between *two successive transits* on that part of the meridian which contains the zenith. Transits on this part of the meridian are called *upper transits*, while transits on the part of the meridian which contains the *nadir* are called *lower transits*.

The terms *meridian passage* and *culmination* are sometimes used in place of the term *transit*.

Besides *sidereal time*, we have *solar time*.

*Apparent solar time* is measured in terms of an *apparent solar day*.

An *apparent solar day* is the interval between two successive upper transits of the *center of the sun* over the meridian of the observer.

These successive returns of the real sun have not always equal intervals between them: first, because the sun does not move in the plane of the equinoctial, but in the ecliptic, which is inclined at an angle of  $23^{\circ} 27'$  to the equinoctial; and, second, because the sun's movement in the ecliptic is not *uniform*. Thus, when the earth is nearest to the sun it moves in its orbit a little over  $61'$  daily, or, considering the earth as still, *the sun moves in the ecliptic* the same amount; but when the earth and sun are farthest from one another, the sun moves in the ecliptic about  $57'$  daily, and, at all other times, at rates varying between these two amounts.

To secure an invariable unit of time, *mean solar time* is used, measured in terms of the *mean solar day*, which is equal in length to the *average* of all the apparent solar days of the year.

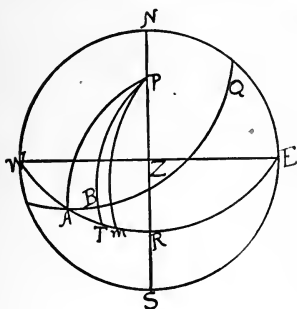
*Mean solar time* is supposed to be regulated by the movements of a fictitious sun, moving in the equinoctial or celestial equator, at a rate which is the average or *mean* rate of movement of the true sun in the ecliptic. If the imaginary or mean sun and the true sun are supposed to start from the same circle of declination, and return to the same circle at the end

of the year, in the interval they are sometimes on the same circle of declination, but generally on different circles, the mean sun being sometimes ahead of the true sun and sometimes behind it.

The *equation of time* is the difference between time measured by the mean sun and time measured by the real sun. This equation of time for every day is always to be found in the Nautical Almanac on pages I and II of each month.

To illustrate, by a figure, the meanings of *sidereal time*, *apparent solar time*, *mean solar time*, and the *equation of time*.

Let  $NWSE$  represent the horizon;  $P$  the pole;  $WRE$  the celestial equator or equinoctial;  $A$  the first point of Aries; and  $ABQ$  the ecliptic.



Let  $B$  represent the place of the true sun on the ecliptic, and  $m$  the place of the mean sun on the equinoctial. Draw circles of declination,  $PBT$  and  $Pm$ .

*Sidereal time* is represented by the angle  $RPA$ , or by its measuring arc  $RA$ . *Apparent solar time* is the angle  $RPB$ , or its measuring arc  $RT$ . *Mean solar time* is  $RPm$ , or the arc  $Rm$ . *The equation of time* is  $mPT$ , or arc  $mT$ .

Thus we may define time by angles measured from the celestial meridian westward.

*Sidereal time* is the angle at the pole of the equi-



noctial between the meridian and a circle of declination passing through the first point of Aries.

*Apparent solar* time is the angle at the pole between the meridian and a circle of declination passing through the center of the *true* sun.

*Mean solar* time is the angle at the pole between the meridian and a circle of declination passing through the position of the *mean* sun.

A *sidereal clock* is adjusted so as to mark 24 hours between two successive transits of the first point of Aries.

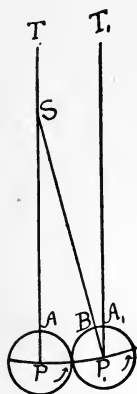
A *mean solar* clock is adjusted to mark 24 hours between two successive transits of the *mean* sun.

Clocks and watches in ordinary use are adjusted to *mean solar time*.

**45.** The daily motion of the mean sun, in the equinoctial, is found to be  $59' 8''.33$ . This is easily determined from the time it takes the true and the mean suns, starting from the meridian of any point, to return to the same meridian. This time is found to be 365.2422 mean solar days, during which the mean sun travels through a complete circle, or  $360^\circ$ . In one day, therefore, it would travel through  $\frac{360}{365.2422}^\circ$ , or  $59' 8''.33$ .

**46.** In order to find the arc described by a meridian of the earth in a mean solar day, let  $P$  and  $P_1$  represent two positions of the center of the earth in its orbit, separated by an interval of time equal to a mean solar day.

Suppose a plane to be passed through the celestial equator; and that the small circles represent the



terrestrial equator of the earth in its two positions; and  $S$  to be the position of the mean sun.  $PA$  and  $P_1A_1$  will be the two projections of the same meridian. As the fixed stars are at such immense distances from the earth, rays of light from such a star, represented by  $TA$  and  $T_1A_1$ , would fall in parallel lines on the earth, in its two positions.

Thus, the meridian  $PA$ , having the light from the star on it, in its first position, would receive the same light in its second position  $P_1A_1$ , having in the interval made a complete rotation, or having gone through an arc of  $360^\circ$ .

Now if  $S$ , on the line  $TA$ , be supposed to be the position of the mean sun, we join  $SP_1$ . Since by Art. 45  $PP_1$  is  $59' 8''.33$ , the angle  $PSP_1$  is also  $59' 8''.33$ . Therefore the alternate angle  $SP_1T_1$  is an angle of  $59' 8''.33$ , and the arc  $AB$  is an arc of  $59' 8''.33$ ; that is, the earth in passing from  $P$  to  $P_1$  in its rotation on its axis, carries the meridian  $PA$  past its position  $P_1A_1$  to the position  $P_1B$ , and, therefore, the meridian moves through an arc of  $360^\circ 59' 8''.33$  in a mean solar day, or  $59' 8''.33$  more than in a sidereal day.

47. In a *sidereal day* of 24 hours the meridian of any place on the earth revolves through  $360^\circ$ . In *one hour* it passes through  $\frac{360^\circ}{24} = 15^\circ$ ;

in one minute it passes through  $\frac{15^\circ}{60} = \frac{1}{4}^\circ = 15'$ ;

in one second it passes through  $\frac{15'}{60} = 15''$ ;

consequently, in passing through an arc of  $59' 8''.33$ , it takes an amount of time equal to  $(\frac{59}{15})$  m. +  $(\frac{8.33}{15})$  s., or equal to 3 m. 56.555 s.

In a *mean solar day* of 24 hours, the meridian of any place revolves through  $360^\circ 59' 8''.33$ . A day of 24 hours of mean solar time is therefore longer than a day of 24 hours of sidereal time by the amount of time (sidereal) which it takes the meridian to pass through an arc of  $59' 8''.33$ ; that is, 3 m. 56.555 s. Therefore, 24 h. mean solar time = 24 h. 3 m. 56.555 s. sidereal time. Thus the sidereal day is shorter than a mean solar day.

48. *To convert sidereal time into mean solar time, and mean solar time into sidereal time.*

Let  $S_t$  = any interval of sidereal time, and  $M_t$  = the same interval expressed in mean solar time.

As the sidereal day is shorter than the mean solar day, a given interval of time will have *more* sidereal hours in it than solar hours, and the ratio of the *hours sidereal* to the *hours mean solar* will be the ratio between the number of hours, minutes, and seconds in a sidereal day, and the 24 hours in a mean solar day.

$$\text{Thus } \frac{S_t}{M_t} = \frac{24 \text{ h. } 3 \text{ m. } 56.555 \text{ s.}}{24 \text{ h.}} = 1.0027379,$$

$$\text{and } \frac{M_t}{S_t} = \frac{24 \text{ h.}}{24 \text{ h. } 3 \text{ m. } 56.555 \text{ s.}} = 0.9972697.$$

$$\therefore S_t = M_t \times 1.0027379 = M_t + .0027379 M_t,$$

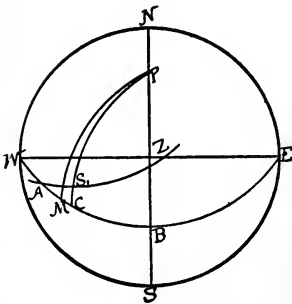
$$\text{and } M_t = S_t \times 0.9972697 = S_t - .0027303 S_t.$$

By means of these formulæ the tables of the Nautical Almanac, and those in Bowditch's Tables, for converting sidereal into mean solar time or mean solar into sidereal time, can be computed.

**49.** To convert a given mean solar time into apparent solar time; and, conversely, to convert given apparent time into mean time; given also the equation of time.

**Ex. 1.** Let mean time be 3 h. 14 m.; and the equation of time be 3 m. 4 s., to be *subtracted*. Required apparent time.

$$\begin{aligned} \text{mean time} &= 3 \text{ h. } 14 \text{ m.} \\ \text{equation of time} &= \frac{3 \text{ m. } 4 \text{ s.}}{\phantom{0}} \\ \text{apparent time} &\Rightarrow 3 \text{ h. } 10 \text{ m. } 56 \text{ s.} \end{aligned}$$



To illustrate this example by a figure, suppose in addition to the given terms, the declination of the sun is  $15^\circ$  N.

Let *NWSE* be the plane of the horizon; *Z* the zenith; *P* the pole; and *WBE* the celestial equator; *AS<sub>1</sub>* the

ecliptic;  $S_1$  the center of the true sun;  $M$  the position of the mean sun on the equinoctial.

Through  $S_1$  draw the circle of declination  $PS_1C$ ; and draw  $PM$  to  $M$ .  $S_1C = 15^\circ$ .

Then  $MPB =$  mean time  $= 3 \text{ h. } 14 \text{ m.}$

$S_1PM =$  equation of time  $= \frac{3 \text{ m. } 4 \text{ s.}}{}$

$S_1PB =$  apparent time  $= 3 \text{ h. } 10 \text{ m. } 56 \text{ s.}$

Ex. 2. Let apparent time be 4 h.; and equation of time be 2 m. 56 s., to be added; and declination of sun be  $20^\circ \text{ N}$ . Required  $M_t$ . In figure above,  $S_1C = 20^\circ$ .

apparent time  $= S_1PB = 4 \text{ h.}$

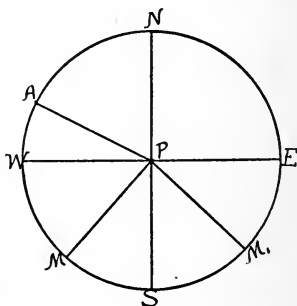
equation of time  $= S_1PM = \frac{2 \text{ m. } 56 \text{ s.}}{}$

$M_t = MPB = 4 \text{ h. } 2 \text{ m. } 56 \text{ s.}$

Sometimes the equation of time is additive, and at other times subtractive. It is given for every day of the year, on pages I and II (for the month), in the Nautical Almanac, and whether additive or subtractive.

50. Given *mean time*, and the *right ascension* of the mean sun, to find *sidereal time* at any place; that is, the *right ascension of the meridian* of the observer.

Let  $NWSE$  represent the plane of the equinoctial;  $NPS$  the projection on it of the celestial meridian;  $A$  the position of the first point of Aries; and  $M$  the position of the mean sun. (Def. pages 76 and 77.)



$$(1) S_t = SPA = MPA + SPM$$

= right ascension of mean sun + mean time.

If  $M_1$  be position of mean sun,

$$S_t = SPA = M_1PA - M_1PS.$$

But  $M_1PS = 360^\circ$  (or 24 h.) – angle measured  
by  $SANM_1 = 24$  h. – mean time.

$\therefore S_t = \text{R.A. mean sun} - (24 \text{ h.} - \text{mean time}), \text{ i.e.}$

$$(2) S_t = \text{R.A. of mean sun} + \text{mean time} - 24 \text{ h.}$$

From equations (1) and (2) we see that sidereal time = R.A. mean sun + mean time, but that when the sum of R.A. mean sun and mean time is greater than 24 h., we subtract 24 h. from that sum.

Ex. 1. Given  $M_t = 7$  h. 10 m. and R.A. mean sun = 2 h. 38 m. 42 s. Find sidereal time.

$$S_t = 2 \text{ h. } 38 \text{ m. } 42 \text{ s.} + 7 \text{ h. } 10 \text{ m.} = 9 \text{ h. } 48 \text{ m. } 42 \text{ s.}$$

Ex. 2. Given mean time 10 h. 32 m. 40 s. and R.A. mean sun = 18 h. 45 m. 35 s. Find sidereal time.

$M_t$	= 10 h. 32 m. 40 s.
R.A. mean sun	= 18 h. 45 m. 35 s.
	<hr style="width: 100%;"/>
Sid. time	= 29 h. 18 m. 15 s. – 24 h.
	= 5 h. 18 m. 15 s.

**51.** To convert *sidereal time* into *mean time*; given the right ascension of the mean sun.

Since by the preceding article *sidereal time* = R.A. mean sun + mean time, or = R.A. mean sun + mean time – 24 h.



Thus it will be seen that to convert civil time into astronomical time, *the P.M. is dropped if the given civil time is after noon*; but if the time is A.M., 12 hours is added to the given civil time and the date is changed to the preceding day.

Ex. 1. Given civil time = 3 h. 10 m. P.M., August 10.  
Astronomical time = 3 h. 10 m., August 10.

Ex. 2. Given civil time = January 8, 10 h. 15 m. A.M.  
Add 12 h., drop the A.M., and astronomical time = January 7, 22 h. 15 m.

Conversely, to convert *astronomical time into civil time*.

If the given time is *under 12 hours*, put on P.M.

If the given time is *over 12 hours*, subtract from it 12 hours, add A.M. to the remainder, and add *one day* to the *date*.

Thus, January 10, 4 h. 15 m. astronomical time = January 10, 4 h. 15 m. P.M. civil time.

February 11, 17 h. 16 m. astronomical time = February 12, 5 h. 15 m. A.M. civil time.

**53.** In every problem of Nautical Astronomy it is necessary to find either the apparent or mean time, at Greenwich, of the instant of taking an observation; since the calculated positions of the heavenly bodies are made for definite times at the meridian of Greenwich. These positions, with the definite times corresponding, are published in the Nautical Almanac.

**54.** The *hour angle of the sun*, at the celestial meridian of any place, is the *local time* of the place.



The hour angle of the sun, at the same instant, at the meridian of Greenwich is the *Greenwich* time.

55. As the earth makes one complete rotation on its axis in 24 hours, so that the same meridian, on its surface, is opposite the first point of Aries, or opposite the same fixed star at the beginning and end of this period of time, and as a complete rotation is measured by  $360^\circ$ , 24 *hours in time* corresponds to  $360^\circ$ , or we can say:

$$24 \text{ h.} = 360^\circ \text{ and } 360^\circ = 24 \text{ h.}$$

$$1 \text{ h.} = 15^\circ \quad 15^\circ = 1 \text{ h.}$$

$$1 \text{ m.} = 15' \quad 1^\circ = 4 \text{ m.}$$

$$1 \text{ s.} = 15'' \quad 1' = 4 \text{ s.}$$

$$1'' = \frac{1}{15} \text{ s.}$$

We can use the *first table* to convert *time* into *angular measure*, and the *second table* to convert *angular measure* into *time measure*.

$$\begin{aligned} \text{Thus } 3 \text{ h. } 10 \text{ m. } 30 \text{ s.} &= 3 \times 15^\circ = 45 \\ &+ 10 \times 15' = 2^\circ 30' \\ &+ 30 \times 15'' = \quad \quad 7' 30'' \\ &= \underline{47^\circ 37' 30''} \end{aligned}$$

$$\text{Again, } 48^\circ 15' 38'' = 3 \text{ h. } 13 \text{ m. } 2\frac{8}{15} \text{ s.}$$

$$\text{For } 48^\circ = 3 \text{ h. } 12 \text{ m.}$$

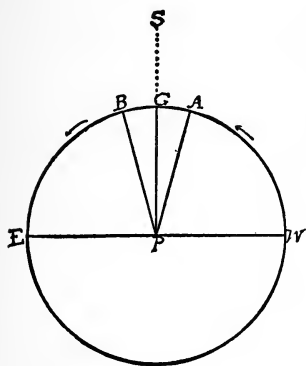
$$15 \times 4 \text{ s.} = 1 \text{ m.}$$

$$38 \times \frac{1}{15} \text{ s.} = \underline{\quad \quad \quad} 2\frac{8}{15} \text{ s.}$$

$$= 3 \text{ h. } 13 \text{ m. } 2\frac{8}{15} \text{ s.}$$

56. In the case of a mean solar day, it was shown in Art. 46, that the meridian of any place moved through an arc of  $360^{\circ} 59' 8.''33$  during 24 mean solar hours. If we suppose 24 meridians drawn on the earth's surface, these meridians will be each  $15^{\circ}$  apart, and, in the rotation of the earth on its axis, will follow each other at an *hour's interval*; so that we can use the tables in the preceding article to convert mean solar *time* into angular *measure*, or angular *measure* into time *measure*.\*

The same tables will give the relation of *apparent solar time* to *angular measure*.



57. These facts have an important bearing in the determination of longitude by means of time. This will be understood by means of a figure.

Let  $GWE$  be the plane of the earth's equator,  $P$  the projection of the pole on that plane,  $PG$  the projection of the meridian of

\* As each meridian between two transits of the sun passes through an arc of  $360^{\circ} 59' 8.''33$ , on first thought it might seem that in order to make intervals correspond to hours, the space to equal *one* hour should be  $15^{\circ} 2' +$ . The difficulty will be cleared by remembering that though it is true each meridian moves in *space*  $15^{\circ} 2' +$  for an hour, before it comes to the position occupied by the meridian immediately preceding it, *all* the meridians here spoken of are  $15^{\circ}$  *apart* on the earth, corresponding to the division of a great circle of  $360^{\circ}$  by 24.

Greenwich,  $PA$  and  $PB$  the projections of the meridians of two places, each  $15^\circ$  from the meridian  $PG$ . If the sun is on the line  $PG$  produced at 12 noon, as the direction of the arrows shows the direction of the earth's rotation to be from W. to E.,  $PA$  will be  $15^\circ$  west, and  $PB$   $15^\circ$  east of  $PG$ . Consequently, when it is 12 noon at any place on the meridian  $PG$ , it will be 11 A.M. at any place on the meridian  $PA$ , and 1 P.M. at any place on the meridian  $PB$ ; for there is an hour's interval of time required to bring  $PA$  to the place of  $PG$  and  $PG$  to the place of  $PB$ .

Now the *longitude* of any place on  $PA$  is  $15^\circ$  W., and the longitude of any place on  $PB$  is  $15^\circ$  E. of Greenwich :

consequently, 1 h. =  $15^\circ$  dif. of longitude ;

1 m. =  $15'$  dif. of longitude ;

1 s. =  $15''$  dif. of longitude ;

or,  $15^\circ$  dif. of longitude = 1 h. dif. in time ;

$1^\circ$  dif. of longitude = 4 m. dif. in time ;

$1'$  dif. of longitude = 4 s. dif. in time ;

$1''$  dif. of longitude =  $\frac{1}{15}$  s. dif. in time.

## CHAPTER VI

## THE NAUTICAL ALMANAC

58. As the calculated positions of the heavenly bodies, recorded in the Nautical Almanac, are given in Greenwich time, the relations established in the preceding chapter between time and angular measure, and between time and difference of longitude, become important in determining the *Greenwich date* of any observation.

The *Greenwich date* is the *apparent or mean time* at *Greenwich*, corresponding to the time at which an observation of a heavenly body is taken at any other place on the earth.

Ex. 1. Given ship time June 8, 8 h. 16 m. P.M. (mean time), and longitude  $40^{\circ} 18' W$ . Required the Greenwich date.

$$\begin{array}{r} \text{ship time June 8} \quad 8 \text{ h. } 16 \text{ m.} \\ \text{long. } 40^{\circ} 18' W. \text{ reduced to time} = \underline{2 \text{ h. } 41 \text{ m. } 12 \text{ s.}} \\ \text{Ans. Greenwich, June 8} \quad 10 \text{ h. } 57 \text{ m. } 12 \text{ s.} \end{array}$$

The time of an observation is always expressed as *astronomical time* (Art. 52).

Ex. 2. Given ship time Jan. 18, 3 h. 20 m. A.M., and longitude  $43^{\circ} 25' E$ . Required Greenwich date.

$$\begin{array}{r} \text{ship time} = \text{Jan. } 17 \quad 15 \text{ h. } 20 \text{ m.} \\ \text{long. in time} = \underline{2 \text{ h. } 53 \text{ m. } 40 \text{ s.}} \\ \text{Ans. Greenwich, June 17} \quad 12 \text{ h. } 26 \text{ m. } 20 \text{ s.} \end{array}$$

59. *From the Nautical Almanac, to take the declination of the sun for any place and date, the longitude of the place being given.*

Ex. 1. Required sun's declination for Jan. 3, 1893, 8 h. 15 m. A.M., mean time, at a place in longitude  $42^{\circ} 18' W.$

ship, Jan. 2	20 h. 15 m.
long. in time	<u>2 h. 49 m. 12 s.</u>
Greenwich, Jan. 2	23 h. 4 m. 12 s. = 23.07 h.
	= Jan. 3 — 0.93 h.

Jan. 3, dif. for 1 h. = $15''.3$	Jan. 3, sun's
<u>.93</u>	dec. at M.N. = $22^{\circ} 46' 46'' S.$
459	<u>14.2</u>
<u>1377</u>	$22^{\circ} 47' 00''.2 S.$
$14''.229$ to be added.	

In this example, the correction for 0.93 h. we *add* to  $22^{\circ} 46' 46''$ , because, as the declination is S. and *decreasing* S., that is, tending N., it must be further S. 0.93 h. *before noon* than it is at noon.

Ex. 2. In longitude  $72^{\circ} 54' W.$ , on June 15, 1897, at 4.30 P.M., mean time, it is required to find the sun's declination.

ship, June 15	4 h. 30 m.
long.	<u>5 h. 51 m. 36 s.</u>
Greenwich, June 15	10 h. 21 m. 36 s. = 10.36 h.

sun's declination mean noon, June 15 =  $23^{\circ} 20' 33''.7 N.$   
 correction =  $10.36 \times 5''.66 = 58''.6 +$   
 sun's declination at time of observation =  $23^{\circ} 21' 32''.3 N.$

difference for 1 h. 15th = $5''.87$
difference for 1 h. 16th = $4''.84$
decrease 24 h. = $1''.03$



Ex. 1. In longitude  $56^{\circ} 10' W.$ , March 3, 1897, 6 h. 15 m. P.M., mean time, it is required to find the *equation* of time.

ship, March 3	6 h. 15 m.
longitude	<u>3 h. 44 m. 40 s.</u>
Greenwich, March 3	9 h. 59 m. 40 s. = 9.994 h.

dif. 1 h. = 0.541 s.	eq. of time = 12 m. 0.75 s.
<u>9.99</u>	correction <u>5.40</u>
4869	11 m. 55.35 s. = eq. of time.
4869	
<u>4869</u>	
5.40458 to be subtracted.	

If it were required in this example to obtain apparent time, we subtract the 11 m. 55 s. from mean time. Thus:

March 3, 1897, 6 h. 15 m.	P.M. mean time
equation of time	<u>11 m. 55 s.</u>
March 3, 1897, 6 h. 3 m. 5 s.	P.M. apparent time

Ex. 2. Given longitude  $75^{\circ} 18' W.$ , Sept. 13, 1897, 6 h. 30 m. A.M., apparent time. Required equation of time and corresponding mean time.

ship, Sept. 12	18 h. 30 m.
longitude	<u>5 h. 1 m. 12 s.</u>
Greenwich, Sept. 12	23 h. 31 m. 12 s.
Sept. 12	23.52 h. = Sept. 13 - 0.48 h.
eq. of time, Sept. 13, apparent noon =	4 m. 16.73 s.
$0.882 \times 0.48 =$ correction	<u>    - .42</u>
eq. of time to be <i>subtracted</i> =	4 m. 16.31 s.
apparent time	<u>6 h. 30 m.</u> A.M.
<i>Ans.</i> Sept. 13, 1897	6 h. 25 m. 43.69 s.   A.M.

In all the foregoing examples the general method of arriving at the required result is :

1. *Express the ship time in astronomical time.*
2. *Find the corresponding Greenwich date.*
3. *Take the required quantity opposite the nearest Greenwich noon, and apply corrections corresponding to the number of hours by which the given time exceeds or falls short of this nearest noon.*

**61.** Given *mean solar time* and *the longitude* ; by means of the Nautical Almanac, to find the corresponding *sidereal time* (Art. 50).

Thus, Jan. 20, 1895, 3 h. 19 m. P.M., mean time, in longitude  $48^{\circ} 40' W.$ , it is required to find the sidereal time.

ship, Jan. 20	3 h. 19 m.	
longitude	3 h. 14 m. 40 s.	
	6 h. 33 m. 40 s.	
Greenwich, Jan. 20		

Jan. 20, 1895, Greenwich mean noon :

$$\text{R.A. mean sun} = 19 \text{ h. } 58 \text{ m. } 27 \text{ s.}$$

Table 9, Bowditch :

correction for 6 h. 33 m. =	1 m. 4.56 s.	
correction for 40 s. =	. 0.11	
	R.A.M. $\odot$ = 19 h. 59 m. 31.67 s.	
	M.T. 3 h. 19 m.	
	sidereal time = 23 h. 18 m. 31.67 s.	



62. Given *apparent solar time* and the *longitude*; from the Nautical Almanac, to obtain the *corresponding sidereal time*.

1. Convert *apparent* into *mean time*.
2. Proceed as in previous article to convert *mean time* into *sidereal time*.

Ex. July 15, 1895, 6 h. 14 m. A.M., apparent time, in longitude  $20^{\circ} 12' E.$ , required corresponding sidereal time.

ship apparent time, July 14	18 h. 14 m.
longitude	1 h. 20 m. 48 s.
Greenwich apparent time, July 14	<u>16 h. 53 m. 12 s.</u>
July 14, 16.887 h. = July 15 - 7.113 h.	
July 15, noon, equation of time =	5 m. 41.34 s.
correction = $0.26 \text{ s.} \times 7.113 =$	1.85 s.
eq. of time to be added to apparent time =	<u>5 m. 39.49 s.</u>
apparent time =	<u>18 h. 14 m.</u>
ship mean time =	18 h. 19 m. 39.49 s.
longitude =	1 h. 20 m. 48 s.
Greenwich mean time, July 14 =	<u>16 h. 58 m. 51.49 s.</u>
R.A.M. sun, July 14, noon =	7 h. 28 m. 24.34 s.
correction for 16 h. 58 m. =	2 m. 47.23 s.
correction for 51.5 s. =	<u>0.14 s.</u>
R.A.M. $\odot =$	7 h. 31 m. 11.71 s.
ship mean time =	<u>18 h. 19 m. 39.49 s.</u>
	<u>25 h. 50 m. 51.2 s.</u>
sidereal time =	1 h. 50 m. 51.02 s.

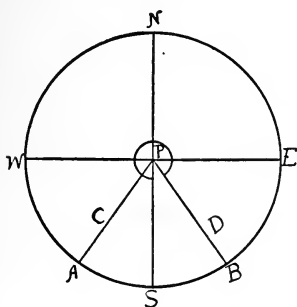
## CHAPTER VII

## THE HOUR ANGLE

The *hour angle* of any celestial body is the *angle*, at the nearer *celestial pole*, made by the *celestial meridian* of the place with the *circle of declination* which passes through the body.

*Hour angles* are measured westward from the meridian from 0 h. to 24 h.

Let the figure represent the plane of the equinoctial,  $P$  the projection of the celestial pole, and  $PA$



and  $PB$  the projections of circles of declination,  $PA$  being to the W. and  $PB$  to the E. of the meridian  $NPS$ .

If  $C$  and  $D$  represent the positions of two heavenly bodies,  $SPA$ , measured by the arc  $SA$ , is the hour angle of  $C$ , and the *salient angle*

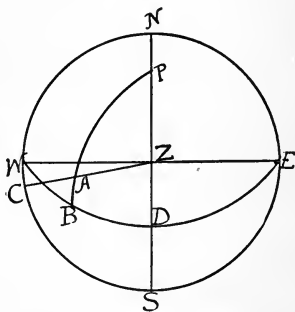
$SPB$ , measured by the arc  $SWNEB$ , is the hour angle of  $D$ .

If  $C$  and  $D$  represent two positions of the sun, then  $SPA$  and  $SPB$  would be apparent *solar time*.  $SPA$  and  $SPB$  would be mean solar time if  $A$  and  $B$  represented the positions of the mean sun.

Also if  $A$  and  $B$  represented two positions of the first point of Aries, the angles  $SPA$  and  $SPB$  would be *sidereal* time (defs. pages 76, 77).

63. *Given the altitude, the declination of a heavenly body, and the latitude of the place of observation; to find the hour angle of the body.*

Let the figure represent the plane of the horizon;  $NS$  the projection on it of the meridian; and  $Z$  the projection of the zenith of the observer. Let  $P$  be the elevated or nearer celestial pole;  $A$  the position of a heavenly body; and let  $WDE$  be the equinoctial. Draw the circle of declination  $PAB$ , and the circle of altitude  $ZAC$ .



Then  $AC$  = the altitude of  $A$ ;

$AB$  = the declination of  $A$ ;

$ZD$  = latitude of the observer.

Consequently, in the triangle  $APZ$ , in order to find the hour angle  $DPB$ , we have given :

$$ZA = 90^\circ - AC = 90^\circ - \text{altitude,}$$

$$PA = 90^\circ - AB = 90^\circ - \text{declination,}$$

and  $PZ = 90^\circ - ZD = 90^\circ - \text{latitude};$

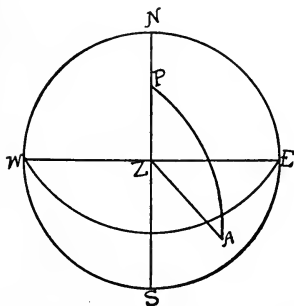
that is, to find  $P$ , in the triangle  $APZ$ , we have the three sides given.

Ex. 1. Given, in lat.  $41^{\circ} 24' N.$ , the declination of Venus =  $24^{\circ} 19' N.$ , and the altitude =  $24^{\circ} 14'$ . Find the hour angle.

In the figure  $ZA = 90^{\circ} - 24^{\circ} 14' = 65^{\circ} 46'$ .  $PA = 90^{\circ} - 24^{\circ} 19' = 65^{\circ} 41'$ ,  $PZ = 90^{\circ} - 41^{\circ} 24' = 48^{\circ} 36'$ . Denoting the sides of the triangle by  $a, p,$  and  $z, a = 48^{\circ} 36', p = 65^{\circ} 46', z = 65^{\circ} 41'$ ; we can solve for  $P$  by the formula,

$$\begin{aligned} \sin \frac{1}{2} P &= \sqrt{\frac{\sin(s-a) \sin(s-z)}{\sin a \sin z}} \\ &= \sqrt{\sin(s-a) \sin(s-z) \operatorname{cosec} a \operatorname{cosec} z} \\ a &= 48^{\circ} 36' & \log \operatorname{cosec} &= 10.12487 \\ z &= 65^{\circ} 41' & \log \operatorname{cosec} &= 10.04035 \\ p &= 65^{\circ} 46' \\ s &= \frac{180^{\circ} 3'}{2} \\ &= 90^{\circ} 1' 30'' \\ s-a &= 41^{\circ} 25' 30'' & \log \sin &= 9.82062 \\ s-z &= 24^{\circ} 20' 30'' & \log \sin &= 9.61508 \\ & & & \underline{2) 19.60092} \\ \log \sin 39^{\circ} 10\frac{1}{2}' &= 9.80046 = \log \sin \frac{1}{2} P \\ \therefore P &= 78^{\circ} 20\frac{2}{5}' = 5 \text{ h. } 13 \text{ m. } 21\frac{3}{5} \text{ s.} \end{aligned}$$

Ex. 2. In lat.  $41^{\circ} 23' N.$ , the altitude of the sun was found to be  $26^{\circ} 38' 44''$ , and its declination to be  $19^{\circ} 20' 26'' S.$  Required the hour angle, supposing the sun to be east of the meridian; that is, that the observation was taken in the morning.



$$\begin{aligned} a &= PZ = 48^{\circ} 37' \\ z &= PA = 109^{\circ} 20' 26'' \\ p &= ZA = 63^{\circ} 21' 16'' \\ s &= \frac{221^{\circ} 18' 42''}{2} \\ &= 110^{\circ} 39' 21'' \end{aligned}$$

$$s - a = 62^\circ 2' 21''$$

$$s - z = 1^\circ 18' 55''$$

$$s - p = 47^\circ 18' 5''$$

$$\sin \frac{1}{2} P = \sqrt{\frac{\sin 62^\circ 2' 21'' \times \sin 1^\circ 18' 55''}{\sin 48^\circ 37' \times \sin 109^\circ 20' 26''}}$$

$$\log \sin 62^\circ 2' 21'' = 9.94609$$

$$\log \sin 1^\circ 18' 55'' = 8.36084$$

$$\log \operatorname{cosec} 48^\circ 37' = 0.12476$$

$$\log \operatorname{cosec} 109^\circ 20' 26'' = 0.02523$$

$$\quad \quad \quad 2) 18.45692$$

$$\log \sin \frac{1}{2} 1 \text{ h. } 17 \text{ m. } 56 \text{ s.} = 9.22846$$

$$= \log \sin \frac{1}{2} \text{ acute angle } ZPA,$$

but astronomical time = *salient* angle *ZPA*.

$$\therefore \text{hour angle} = 24 \text{ h.} - 1 \text{ h. } 17 \text{ m. } 56 \text{ s.} = 22 \text{ h. } 42 \text{ m. } 4 \text{ s.},$$

or civil apparent time = 10 h. 42 m. 4 s. A.M.

Ex. 3. Suppose in addition to the data of the preceding example, the longitude of the place of observation was given as  $72^\circ 56' \text{ W.}$ , and it was required to find the *mean* time at the instant of the observation on Nov. 19, 1894, at 10 h. 42 m. 4 s. apparent time.

By definition on page 77 *apparent solar time* is the angle, at the pole, between the meridian and a circle of declination passing through the center of the true sun. Consequently, the answer in the preceding example is *apparent time*, and we have to apply the equation of time for the given date.

$$\text{ship, Nov. 18, } 22 \text{ h. } 42 \text{ m. } 4 \text{ s.}$$

$$\text{long. in time} = 4 \text{ h. } 51 \text{ m. } 44 \text{ s.}$$

$$\text{Greenwich, Nov. 19} = 3 \text{ h. } 33 \text{ m. } 48 \text{ s.} = 3.56 \text{ h.}$$

$$\text{eq. of time, Nov. 19, Green., noon} = 14 \text{ m. } 26.88 \text{ s. sub.}$$

$$(\text{dif. } 1 \text{ h.}) 0.574 \text{ s.} \times 3.56 = 2.04 \text{ s.}$$

$$\text{equation of time} = 14 \text{ m. } 24.84 \text{ s. sub.}$$

$$\text{apparent time} = 10 \text{ h. } 42 \text{ m. } 4 \text{ s. A.M.}$$

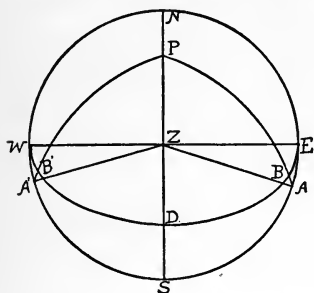
$$\text{mean time} = 10 \text{ h. } 27 \text{ m. } 39.16 \text{ s. A.M.}$$

64. To find the time of sunrise or sunset for a given day, at any place on the earth, the latitude and longitude of the place, and the sun's declination for the day being given.

Let the figure represent, as in Art. 63, the projection of the celestial sphere on the plane of the horizon.

Suppose  $A$  to represent the position of the sun on the eastern horizon when it is first visible to an

observer whose zenith is  $Z$ ; and suppose  $A'$  to represent the position of the sun on the western horizon when it is last visible to the same observer.



meridian, the time is *apparent noon*. The angle  $ZPA$ , expressed in time, would give the hours, minutes, and seconds which the sun, in its passage across the heavens, would take to go from its position at  $A$  to its position on *the meridian*. In other words, the angle  $ZPA$  gives the hours, minutes, and seconds of apparent time between sunrise and noon. In the same way, the angle  $ZPA'$  gives the apparent time between noon and sunset, or in common language, the apparent time of sunset. 24 h. — angle  $ZPA$  (expressed in time) would give the *astronomical* apparent time of sunrise. 12 h. — angle  $ZPA$  (expressed in time) would give the *civil* apparent time.

In the preceding figure, the declination  $BA$  is given as S. declination, while the elevated pole  $P$  is supposed to be N.

The zenith distance to  $A$ , a point on the horizon, is  $90^\circ$ . But as the time of sunrise is calculated from the instant when the *upper rim* of the sun is first visible, and as measurements are made to the center of the sun,  $16'$  is added to  $90^\circ$ , as the center of the sun is about that distance below the horizon. Moreover, as by refraction the sun, though *below* the horizon, is made to appear above it,  $34'$  is added also to  $90^\circ$  for refraction. Consequently, for problems in sunrise and sunset the distances  $ZA$  and  $ZA'$  are generally taken to be each  $90^\circ 50'$ .

Though the declination of the sun is continually changing, so that the declination is *not exactly the same* at sunrise and sunset, yet the change is so small that it is assumed to be the same both at those times and at noon. For convenience of calculation, therefore, the declination of the sun for *noon* is used in the solution of problems in sunrise and sunset.

Ex. 1. January 28, 1898, in lat.  $42^\circ 18' N.$ , long.  $72^\circ 55\frac{3}{4}' W.$ , it is required to find the *apparent time* of sunrise and sunset.

$$\text{local time at noon} = 0 \text{ h. } 0 \text{ m. } 0 \text{ s.}$$

$$\text{long. in time} = 4 \text{ h. } 51 \text{ m. } 43 \text{ s.}$$

$$\begin{aligned} \text{Greenwich, Jan. 28} &= 4 \text{ h. } 51 \text{ m. } 43 \text{ s.} \\ &= 4.86 \text{ h.} \end{aligned}$$

$$\text{declination of sun, Greenwich noon January 28} = 18^\circ 6' 25''.8 \text{ S.}$$

$$\text{cor.} = 39''.85 \times 4.86 = \underline{3' 13''.7 \text{ N.}}$$

$$\text{declination of sun at local apparent noon} = 18^\circ 3' 12''.1 \text{ S.}$$

hourly difference of declination of sun =  $39''.85$  N.

$$\begin{array}{r} 4.86 \\ \hline 23910 \\ 31880 \\ \hline 15940 \\ \hline 193''.6710 = 3' 13''.7 \end{array}$$

In preceding figure,

$$\begin{aligned} PZ = a &= 90^\circ - 41^\circ 18' &= 48^\circ 42' \\ PA = z &= 90^\circ + 18^\circ 3' 12'' &= 108^\circ 3' 12'' \\ ZA = p &= 90^\circ + 50' &= 90^\circ 50' \\ s &= \frac{247^\circ 35' 12''}{2} \\ &= 123^\circ 47' 36'' \\ s - a &= 75^\circ 5' 36'' \\ s - z &= 15^\circ 44' 24'' \\ s - p &= 32^\circ 57' 36'' \end{aligned}$$

$$\sin \frac{1}{2}P = \sqrt{\sin(s-a) \sin(s-z) \operatorname{cosec} a \operatorname{cosec} z.}$$

$$\begin{aligned} \log \sin 75^\circ 5' 36'' &= 9.98513 \\ \log \sin 15^\circ 44' 24'' &= 9.43341 \\ \log \operatorname{cosec} 48^\circ 42' &= 10.12421 \\ \log \operatorname{cosec} 108^\circ 3' 12'' &= 10.02191 \\ &= \underline{2)19.56466} \end{aligned}$$

$$\log \sin 37^\circ 17'' \frac{3}{16} = 9.78233 = \log \sin \frac{1}{2}P$$

$P = 74^\circ 34' \frac{6}{16} = 4 \text{ h. } 58 \text{ m. } 17\frac{1}{2} \text{ s.} =$  apparent time of sunset.

$12 \text{ h.} - 4 \text{ h. } 58 \text{ m. } 17\frac{1}{2} \text{ s.} = 7 \text{ h. } 1 \text{ m. } 42\frac{1}{2} \text{ s.} =$  apparent time of sunrise.

Ex. 2. In preceding example, required the *mean times* of sunrise and sunset; also eastern standard time of sunrise and sunset.

January 28, equation of time Greenwich noon = 13 m. 13.97 s.  
 difference for 1 h. =  $0.457 \text{ s.} \times 4.86 = \underline{2.22+}$   
 local equation of time at noon = 13 m. 16.19 s.



$$\begin{array}{r}
 0.457 \\
 \underline{4.86} \\
 2742 \\
 3656 \\
 \underline{1828} \\
 2.22102
 \end{array}$$

local mean time of apparent noon = 12 h. 13 m. 16.19 s.

subtract hour angle = 4 h. 58 m. 17.5 s.

local mean time of sunrise = 7 h. 14 m. 58.69 s. A.M.

local mean time of sunset = 5 h. 11 m. 33.69 s. P.M.

eastern standard time = time of meridian of 75° W.

local meridian = 72° 55 $\frac{3}{4}$  W.

difference = 2° 4 $\frac{1}{4}$

= 8 m. 17 s.

taking 8 m. 17 s. from the mean times calculated above

eastern standard time of sunrise = 7 h. 6 m. 41.69 s. A.M.

eastern standard time of sunset = 5 h. 3 m. 16.69 s. P.M.

In this example we have used the noon equation of time to be applied to time of sunrise and sunset. A more exact calculation would apply the equation of time as derived for the instant of apparent time of sunrise or of sunset.

For sunrise.

Greenwich, 27th 19 h. 1 m. 42 $\frac{1}{2}$  s.

longitude in time 4 h. 51 m. 43 s.

Greenwich, Jan. 27 23 h. 53 m. 25 $\frac{1}{2}$  s.

or Jan. 28 — 0 h. 6 m. 34.5 s. = — .011

eq. of time, Greenwich, noon 13 m. 13.97 s.

correction 0.457 s  $\times$  .011 h. = 0.01

equation of time for sunrise = 13 m. 13.96 s. +

apparent time of sunrise = 7 h. 1 m. 42.5 s.

exact mean time = 7 h. 14 m. 56.46 s. A.M.

For sunset.	Jan. 28	4 h. 58 m. 17.5 s.
	longitude	<u>4 h. 51 m. 43 s.</u>
	Greenwich, Jan. 28	9 h. 50 m. 0.5 s. = 9.83 h.
		0.457
		<u>6881</u>
		4915
		3932
	correction =	<u>4.49231 s.</u>
eq. of time, Greenwich, noon =		13 m. 13.97 s.
	correction	<u>4.49</u>
	equation of time =	13 m. 18.46 s.
apparent time of sunset =		<u>4 h. 58 m. 17.5 s.</u>
exact mean time =		5 h. 11 m. 35.96 s. P.M.

Since the time of sunrise and the time of sunset are generally calculated to the *nearest minute only*, the first method of applying the local noon equation of time is generally used. By comparing the results by the two methods it will be seen that the difference in the answers does not much exceed two seconds.

Ex. 3. June 1, 1898, in latitude  $41^{\circ} 18' N.$ , longitude  $72^{\circ} 55' \frac{3}{4} W.$ , required the eastern standard times of sunrise and sunset.

local noon	0 h. 0 m. 0 s.
longitude	<u>4 h. 51 m. 43 s.</u>
Greenwich, June 1	4 h. 51 m. 43 s.
	= 4.86 h.

Declination of sun.

Greenwich, noon =	22° 6' 0".7 N.
correction $20''.12 \times 4.86 =$	<u>137.8+</u>
declination of sun =	22° 7' 38".5 N.
polar distance =	67° 52' 22"

$$\begin{array}{r}
 \text{equation of time, Greenwich noon} = 2 \text{ m. } 24.55 \text{ s.} - \\
 \text{correction } 0.375 \text{ s.} \times 4.86 \text{ h.} = \quad \quad \quad \underline{1.82 -} \\
 \text{equation of time, local noon} = \quad \quad \quad \underline{2 \text{ m. } 22.73 \text{ s.} -} \\
 \text{apparent noon} = 12 \text{ h.}
 \end{array}$$

$$\text{mean time of apparent noon} = 11 \text{ h. } 57 \text{ m. } 37.17 \text{ s. A.M.}$$

$$\text{deduct for eastern standard time} \quad \quad \quad \underline{8 \text{ m. } 17 \text{ s.}}$$

$$\text{eastern standard time of apparent noon} = 11 \text{ h. } 49 \text{ m. } 20.17 \text{ s. A.M.}$$

Projecting the celestial concave on the celestial meridian.

$$PZ = a = 48^\circ 42' \quad \log \operatorname{cosec} = 10.12421$$

$$PA = z = 67^\circ 52' 22'' \quad \log \operatorname{cosec} = 10.03322$$

$$ZA = p = 90^\circ 50'$$

$$s = \frac{207^\circ 24' 22''}{2} = 103^\circ 42' 11''$$

$$s - a = 55^\circ 0' 11'' \quad \log \sin = 9.91338$$

$$s - z = 35^\circ 49' 49'' \quad \log \sin = 9.76744$$

$$\quad \quad \quad \underline{2) 19.83825}$$

$$\log \sin 56^\circ 6' 33'' = 9.91912\frac{1}{2}$$

$$\quad \quad \quad \underline{08}$$

$$P = 112^\circ 13' 6'' \quad \quad \quad \underline{4\frac{1}{2}}$$

$$= 7 \text{ h. } 28 \text{ m. } 52.4 \text{ s.}$$

$$\text{eastern standard time of apparent noon} = 11 \text{ h. } 49 \text{ m. } 20.2 \text{ s.}$$

$$\text{eastern standard time of sunrise} = 4 \text{ h. } 20 \text{ m. } 27.8 \text{ s. A.M.}$$

$$\text{eastern standard time of sunset} = 7 \text{ h. } 18 \text{ m. } 12.6 \text{ s. P.M.}$$

Ex. 4. Jan. 10, 1898, in latitude  $39^\circ 57' \text{ N.}$ , longitude  $75^\circ 9' \text{ W.}$ , required mean time of sunrise and of sunset.

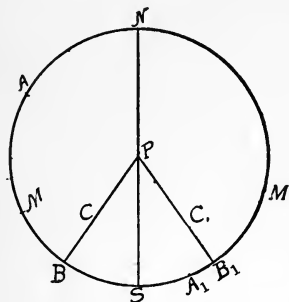
$$\text{Ans. } 7 \text{ h. } 21 \text{ m. } 38 \text{ s. A.M.; } 4 \text{ h. } 54 \text{ m. } 16 \text{ s. P.M.}$$

Ex. 5. May 16, 1898, in latitude  $42^\circ 36' \text{ N.}$ , longitude  $70^\circ 40' \text{ W.}$ , required eastern standard time of sunrise and of sunset.

$$\text{Ans. } 4 \text{ h. } 18 \text{ m. } 44 \text{ s. A.M.; } 6 \text{ h. } 58 \text{ m. } 16 \text{ s. P.M.}$$

**65.** *Given a star's hour angle, to find mean time.*

Let the figure represent the plane of the equinoctial;  $P$  the projection of the pole on the plane;



$C$  the position of the star;  $A$  the position of the first point of Aries; and  $M$  the position of the mean sun.

If  $NPS$  be the projection of the celestial meridian, and  $PCB$  be the projection of the circle of declination passing through  $C$ ,  $SPC$  will be the hour angle of the star, and  $SB$  will measure that angle. Now  $SM = SB + AB - AM$ ; that is, mean time = star's hour angle + R.A. of star - R.A. of mean sun. In the case just given the star is W. of the meridian.

Suppose the star is at  $C'$ , and east of the meridian; that  $A_1$  is first point of Aries, and  $M_1$  is position of mean sun; then  $SM_1 = SB_1 + A_1M_1 - A_1B_1$  or (24 h. - mean time) = (24 h. - star's hour angle) + R.A. mean sun - star's R.A.

$\therefore$  mean time = star's hour angle + R.A. of  
star - R.A. mean sun.

**66.** To find the *mean time at any place*, having given *the hour angle of a star*; the *longitude* of the place; the *date*; and the *approximate local mean time*.

By the previous article we have to add to the hour angle the *star's R.A.*, and from the sum subtract the

*R.A. of the mean sun for the given date and approximate time.*

Ex. 1. Nov. 22, 1891, 7 h. 15 m. P.M., approximate mean time in long.  $87^{\circ} 56'$  W., the hour angle of Aldebaran ( $\alpha$  Tauri), was 18 h. 55 m. 15 s. (E. of meridian). Star's R.A. = 4 h. 29 m. 41.5 s. Required mean time at the place.

ship, Nov. 22 = 7 h. 15 m.

longitude = 5 h. 51 m. 44 s.

Greenwich, Nov. 22 = 13 h. 6 m. 44 s.

Green., Nov. 22, noon, R.A. mean sun = 16 h. 4 m. 44.5 s.

correction for 13 h. 6 m. = 2 m. 9.1 s.

correction for 44 s. = .1 s.

R.A. mean sun at time of observation = 16 h. 6 m. 53.7 s.

star's H.A. = 18 h. 55 m. 15 s.

star's R.A. = 4 h. 29 m. 41.5 s.

23 h. 24 m. 56.5 s.

R.A. mean sun = 16 h. 6 m. 53.7 s.

*Ans.* 7 h. 18 m. 2.8 s. P.M.

Ex. 2. June 23, 1891, at 4 h. 12 m. A.M. mean time, nearly, in long.  $50^{\circ} 15'$  W., the hour angle of  $\alpha$  Lyræ was 3 h. 41 m. W. of meridian. Required mean time. Star's R.A. = 18 h. 33 m. 15.8 s.

ship, June 22 = 16 h. 12 m.

longitude = 3 h. 21 m.

Greenwich, June 22 = 19 h. 33 m.

Green., June 22, noon, sid. time = 6 h. 1 m. 31.55 s.

correction for 19 h. 33 m. = 3 m. 12.69 s.

R.A. mean sun = 6 h. 4 m. 44.24 s.

star's H.A. = 3 h. 41 m.

star's R.A. = 18 h. 33 m. 15.8 s.

22 h. 14 m. 15.8 s.

6 h. 4 m. 44.2 s.

June 22 16 h. 9 m. 31.6 s. ast. time

June 23 4 h. 9 m. 31.6 s. A.M. m. t.

67. Given *mean*, or *apparent* time at place of *given longitude*; to find what star of 1st or 2d magnitude will pass the meridian next after that time.

The solution of this problem is simply to find the sidereal time corresponding to the given time, and then, from list of fixed stars in Nautical Almanac, to choose the star of required magnitude whose right ascension is the next greater than the sidereal time found.

Ex. In long.  $72^{\circ} 56' W.$ , Dec. 7, 1897, at 11 h. 30 m. P.M. mean time, what star of 1st or 2d magnitude passed the meridian shortly after that time?

ship, Dec. 7, 1897 = 11 h. 30 m.

longitude = 4 h. 51 m. 44 s.

Greenwich, Dec. 7 = 16 h. 21 m. 44 s.

Dec. 7, mean noon R.A.M.  $\odot$  = 17 h. 6 m. 3.95 s.

correction for 16 h. 21 m. = 2 m. 41.15 s.

correction for 44 s. = .12 s.

R.A.M. sun = 17 h. 8 m. 45.22 s.

ship, Dec. 7 = 11 h. 30 m.

= 28 h. 38 m. 45.2 s.

= 24 h.

sidereal time or R.A. of meridian = 4 h. 38 m. 5.8 s.

In catalogue of fixed stars (Capella),  $\alpha$  Aurigæ has R.A. 5 h. 9 m. 4.8 s., and is, therefore, star required.

68. To find at what mean time any star will pass a given meridian.

Let the figure represent the plane of the equinoctial;  $P$  the pole;  $NPS$  the celestial meridian;  $A$  the

first point of Aries;  $m$  the position of the mean sun; and  $B$  the position of the star at instant of crossing the meridian.

Then  $mS$

$$= \text{mean time} = AS - Am,$$

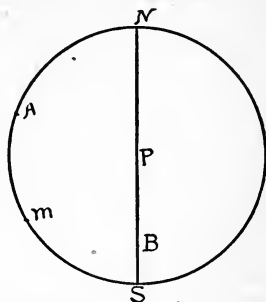
or mean time

$$= \text{sidereal time of star}$$

$$- \text{R.A. of mean sun}$$

$$= \text{R.A. of star}$$

$$- \text{R.A. of mean sun.}$$



Ex. To find at what time Sirius passed the meridian in longitude  $72^{\circ} 56' W.$ , Dec. 8, 1897.

$$\text{R.A. of Sirius} = 6 \text{ h. } 40 \text{ m. } 39 \text{ s.}$$

$$\begin{array}{r} \text{add } 24 \text{ h.} \\ \hline 30 \text{ h. } 40 \text{ m. } 39 \text{ s.} \end{array}$$

$$\text{R.A. of sun (noon)} = 18 \text{ h. } 10 \text{ m. } 0.5 \text{ s.}$$

$$\text{ship approximate mean time} = 13 \text{ h. } 30 \text{ m. } 38.5 \text{ s.}$$

$$\text{longitude} = 4 \text{ h. } 51 \text{ m. } 44 \text{ s.}$$

$$\text{Greenwich, Dec. 8} = 17 \text{ h. } 22 \text{ m. } 22.5 \text{ s.}$$

$$\text{R.A. M.S. noon} = 17 \text{ h. } 10 \text{ m. } 0.5 \text{ s.}$$

$$\text{correction for } 18 \text{ h. } 22 \text{ m.} = 3 \text{ m. } 1.03 \text{ s.}$$

$$\text{correction for } 22.5 \text{ s.} = .06 \text{ s.}$$

$$\text{R.A. M. sun} = 17 \text{ h. } 13 \text{ m. } 1.59 \text{ s. subtract}$$

$$\text{from R.A. Sirius} = 30 \text{ h. } 40 \text{ m. } 39 \text{ s.}$$

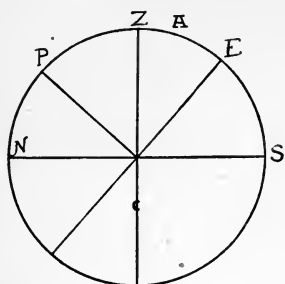
$$13 \text{ h. } 27 \text{ m. } 37 \text{ s. ast. time}$$

$$12 \text{ h.}$$

$$\text{Ans. Dec. 8. } \quad 1 \text{ h. } 27 \text{ m. } 37 \text{ s. } 3 \text{ A.M.}$$

69. To find the *meridian altitude* of a heavenly body for a given place, and whether it will pass N. or S. of the zenith, the declination of the body and the latitude of the place being given.

Ex. 1. At a place in latitude  $42^\circ$  N., it is required to find the meridian altitude of a star whose declination is  $25^\circ$  N.; also whether it passes N. or S. of the zenith.



Let  $NZS$  represent the plane of the celestial meridian;  $P$  the upper or N. pole;  $Z$  the zenith;  $N$  and  $S$  the north and south points of the horizon; and  $E$  the point where the equinoctial intersects the meridian. Let  $AE = 25^\circ$ , then  $A$  is the position of the star at transit. Let  $ZE =$  latitude  $42^\circ$  N.

$$ZA = ZE - AE = 42^\circ - 25^\circ = 17^\circ.$$

$\therefore$  star's transit is south of zenith.

Again, altitude of star  $= AS = ZS - ZA = 90^\circ - 17^\circ = 73^\circ$ .

Ex. 2. Dec. 9, 1897, at what time did  $\alpha$  Orionis pass the meridian of longitude  $72^\circ 56'$  W. in latitude  $42^\circ 18'$  N.; and did it pass N. or S. of zenith? Required its altitude also.

given the declination of star  $= 7^\circ 23' 16''$  N.

R.A. of star  $= 5$  h. 49 m. 40 s.; R.A. M.S.  $= 17$  h. 13 m. 57 s.

R.A. of star  $+ 24$  h.  $= 29$  h. 49 m. 40 s.

R.A. of sun (Greenwich noon)  $= 17$  h. 13 m. 57 s.

mean time (approximately)  $= 12$  h. 35 m. 43 s.

longitude  $= 4$  h. 51 m. 44 s.

Greenwich mean time (approximately)  $= 17$  h. 27 m. 27 s.

R.A. M. sun (Greenwich noon)  $= 17$  h. 13 m. 57 s.

correction for 17 h. 27 m.  $= 2$  m. 51.9 s.

correction for 27 s.  $= .1$  s.

R.A. M. sun  $= 17$  h. 16 m. 49 s.

R.A. of star  $= 29$  h. 49 m. 40 s.

star on meridian  $= 12$  h. 32 m. 51 s.

$= 32$  m. 51 s. after  
midnight Dec. 10



$$\begin{aligned}
 \text{latitude} &= 42^{\circ} 18' \text{ N.} \\
 \text{declination of star} &= 7^{\circ} 23' 16'' \text{ N.} \\
 &\quad \underline{34^{\circ} 54' 44'' \text{ S. of zenith}} \\
 &\quad 90^{\circ} \\
 &\quad \underline{\hspace{1.5cm}} = \text{altitude} \\
 &\quad 55^{\circ} 5' 16''
 \end{aligned}$$

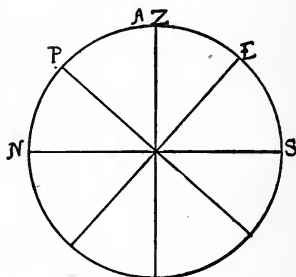
Ex. 3. At what time, Dec. 10, 1897, in latitude  $42^{\circ} 18' \text{ N.}$ , longitude  $72^{\circ} 56' \text{ W.}$ , did  $\eta$  Ursæ Majoris pass the meridian? Was the transit N. or S. of the zenith?

$$\begin{aligned}
 \text{R.A. of star} &= 13 \text{ h. } 43 \text{ m. } 31 \text{ s.} \\
 \text{declination of star} &= 49^{\circ} 49' 2'' \text{ N.}
 \end{aligned}$$

Let  $NPZES$  be the meridian;  $P$  the pole;  $Z$  the zenith;  $A$  be the position of star at transit.

$$\begin{aligned}
 AE &= 49^{\circ} 49' 2'' \\
 ZE &= 42^{\circ} 18' \\
 ZA &= 7^{\circ} 31' 2'' \\
 \text{star N. of zenith} \\
 ZN &= 90^{\circ}
 \end{aligned}$$

$$\text{altitude} = AN = 82^{\circ} 28' 58''$$



To find at what time the star passed the meridian Dec. 10, we must begin *one day back*, and take out the R.A. of  $M. \odot$  for Dec. 9.

$$\begin{aligned}
 \text{thus, R.A. of star} + 24 \text{ h.} &= 37 \text{ h. } 43 \text{ m. } 31 \text{ s.} \\
 \text{R.A. of } M. \odot, \text{ Dec. 9, noon} &= 17 \text{ h. } 13 \text{ m. } 57 \text{ s.} \\
 \text{approximate mean time} &= 20 \text{ h. } 29 \text{ m. } 34 \text{ s.} \\
 \text{longitude} &= 4 \text{ h. } 51 \text{ m. } 44 \text{ s.} \\
 \text{Dec. 10, Greenwich mean time} &= 1 \text{ h. } 21 \text{ m. } 18 \text{ s.} \\
 \text{" " R.A. } M. \odot \text{ noon} &= 17 \text{ h. } 17 \text{ m. } 54 \text{ s.} \\
 \text{correction for } 1 \text{ h. } 21 \text{ m.} &= 13.3 \text{ s.} \\
 \text{correction for } 18 \text{ s.} &= .05 \text{ s.} \\
 \text{R.A. } M. \odot &= 17 \text{ h. } 18 \text{ m. } 7.4 \text{ s.} \\
 \text{R.A. star} &= 37 \text{ h. } 43 \text{ m. } 31 \text{ s.} \\
 \text{Dec. 9} & 20 \text{ h. } 25 \text{ m. } 23.6 \text{ s. ast. time} \\
 \text{Dec. 10} & 8 \text{ h. } 25 \text{ m. } 23.6 \text{ s. A.M.}
 \end{aligned}$$



planes are perpendicular to the plane of the arc  $AB$ .  $EN$  is fixed in position, and its glass is silvered on the half next to the frame of the instrument.  $EN$  is called the *horizon* glass, because through it the horizon is viewed in taking observations.  $CM$  is called the *index* glass. It is entirely silvered (on one face). By means of the index bar,  $CB$ , it is movable about the point  $C$ , which is the center of the arc  $AB$ . When the index bar is at the zero point on the arc  $AB$ , the planes of the two glasses,  $EN$  and  $CM$ , are parallel.

If it is required to find the altitude of any body,  $S$ , above the horizon, the observer looks at the horizon line through the plain part of the glass  $EN$ , and moves the instrument and the index bar till an image of  $S$  reflected from  $CM$  upon  $EN$  appears to coincide with a point upon the horizon.

Let  $K$  be the point of the horizon with which  $S$  appears to coincide. Let  $CM'$  be the position of the index glass and  $CD$  be the position of the index bar when  $K$  and  $S$  appear in coincidence. Join  $SC$ ,  $CN$ , and  $KN$ . Produce  $SC$  and  $KN$  to meet at  $J$ .

$JK$  will represent the plane of the horizon, and the angle  $SJK$  will be the altitude of  $S$ .

Produce  $EN$  to meet  $CD$  (in this case) at  $D$ .

The arc  $DB$  measures the angle  $DCB$ . But  $DCB = NDC$ , since  $EN$  and  $CM$  are parallel.

When a ray of light is reflected from a plane surface, *the angle of incidence is equal to the angle of reflection* :

therefore  $SCH = NCD$ ,

but  $SCH = M' CJ$ ,

these being vertical angles; therefore,

$$NCJ = 2(NCD).$$

Also, since *angle of incidence is equal to angle of reflection*,

$$ENC = DNJ, \text{ but } DNJ = ENK;$$

therefore (1),  $KNC = 2(ENC) = 2[(NCD) + D]$ ,

because  $ENC$  is exterior angle of triangle  $NCD$ .

$$\text{Also (2), } KNC = NCJ + J = 2(NCD) + J;$$

$$\text{consequently, } 2(NCD) + 2D = 2(NCD) + J;$$

$$\text{that is, } D = \frac{1}{2}J;$$

but as  $D = DCB$ , and  $DB$  measures  $DCB$ ,  $DB$  measures half of  $J$ , or half the altitude of  $S$ . The whole arc  $AB$ , however, is so graduated that each *half degree* counts as a *degree*, and the reading of the arc  $DB$  gives the measure of the whole angle  $J$ .

*Index error.* The planes of the index glass and horizon glass should be parallel when the index bar is at the zero point on the graduated arc  $AB$ . The distance, either *on* the arc (that is, to the left of the zero point), or *off* the arc (that is, to the right of the zero point), to which the index bar must be moved to make these planes parallel, is called the index error. This error demands a *correction* for every angle measured.

To determine the index error for any instrument, the simplest method is to measure at successive instants the angle subtended by the sun near the zero point. As the diameter of the sun is the same, these measurements should agree if there is no error, but if they do not agree, there is an error in the instrument. This will be understood by means of the figure.

Let  $AOB$  be a part of the arc of the sextant having the zero point at  $O$ . Suppose that in measuring the diameter of the sun *on the arc* the index bar is moved to  $A$ , and that in measuring the same diameter off the arc the index is moved to  $D$ . Then, denoting the measure of the diameter by  $d$ ,  $AD = 2d$ ; consequently  $B$ , the middle point of  $AD$ , should be the real zero point of the graduated arc.  $OB$  would represent the error, which is *off* the arc, in this case, and the *correction* for the error, called *index correction*, must be *added*.

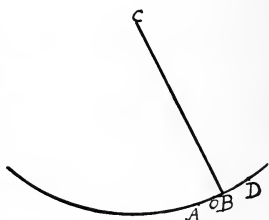
Denote  $OB$  by  $\epsilon$ ; the reading  $OA$  by  $r$ ; the reading  $OD$  by  $r'$ ; then

$$AB = BD,$$

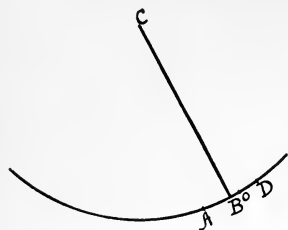
or 
$$AO + OB = OD - OB;$$

that is, 
$$r + \epsilon = r' - \epsilon;$$

therefore, 
$$\epsilon = \frac{r' - r}{2}.$$



If the reading  $AO$ , on the arc, is greater than the reading  $OD$ , off the arc,



since  $AB = BD$ ,

$$r - \epsilon = r' + \epsilon.$$

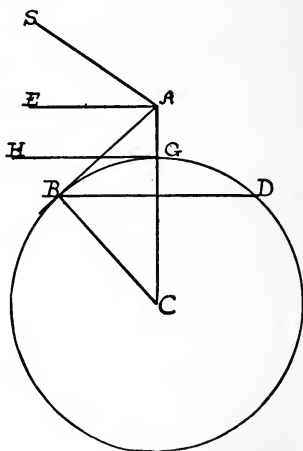
$$\therefore \epsilon = \frac{r - r'}{2}.$$

In this case the *index correction* must be *subtracted*.

71. The *dip* of the horizon is the angle of depression of the *visible* horizon below the horizontal plane of the observer. This depression of the visible horizon is due to the elevation of the eye of the observer above the level of the sea.

Let the figure represent a section of the earth by a plane passed through  $A$ , the point of observation, and  $C$ , the center of the earth.

The small circle, of which  $BD$  is the diameter, would represent the plane of the observer's visible horizon. If  $AE$  be the line in which the plane  $ABC$  intersects



the horizontal plane through  $A$ , then  $EAB$  would be the *dip*, or angle of depression of the visible horizon,  $BD$ , below the horizontal plane of the observer

at  $A$ . If  $S$  be a celestial body, the angle  $SAE$  would be its true altitude,  $SAB$  its measured or observed altitude. *Dip* must always be *subtracted* from the *observed* altitude to obtain the *true* altitude, for  $SAB - EAB = SAE$ .

$AB$  is tangent at  $B$ . Join  $C$  and  $B$  by straight line,  $CB$ .  $EA$  is parallel to tangent at  $G$ , and therefore is perpendicular to  $CA$ .

Angles  $EAB$  and  $ACB$  are complements of  $BAC$  and therefore equal; that is,  $ACB = \text{dip}$ .

Let  $AG = h$  and  $CG = R$ .

$$\begin{aligned} \text{Then } AB &= \sqrt{AC^2 - CB^2} = \sqrt{(R + h)^2 - R^2} \\ &= \sqrt{2Rh + h^2}. \end{aligned}$$

$$\begin{aligned} \therefore \tan \text{dip} = \tan ACB &= \frac{AB}{BC} = \frac{\sqrt{2Rh + h^2}}{R} \\ &= \sqrt{\frac{2Rh + h^2}{R^2}}. \end{aligned}$$

But since  $h$  is small compared with  $R$ ,  $h^2$  may be neglected, and

$$\tan \text{dip} = \sqrt{\frac{2h}{R}} \text{ nearly.}$$

But as the dip is usually a very small angle, and since for a very small angle the circular measure of the angle is approximately equal to the tangent of the angle, we can say

$$\text{circular measure of dip} = \sqrt{\frac{2h}{R}}.$$

$$\text{Now circular measure of dip} = \frac{n\pi}{180}$$

where  $n$  = number of degrees in angle,  $n$  being integral or fractional; therefore reducing to minutes.

$$\frac{60 n\pi}{180 \times 60} = \sqrt{\frac{2h}{R}};$$

or, since  $60 n$  = dip in minutes,

$$\text{dip in minutes} = \frac{10800}{\pi} \sqrt{\frac{2h}{3960 \times 5280}},$$

reducing  $R$  to feet,  $R$  being 3960 miles.

$$\text{Dip in minutes} = \frac{10800 \sqrt{2}}{\pi \sqrt{3960 \times 5280}} \sqrt{h}.$$

$$\log 10800 = 4.03342$$

$$\log \sqrt{2} = 0.15051$$

$$\text{colog } \pi = 9.50285 - 10$$

$$\text{colog } \sqrt{3960} = 8.20115 - 10$$

$$\text{colog } \sqrt{5280} = 8.13868 - 10$$

$$\log 1.063 = 0.02661$$

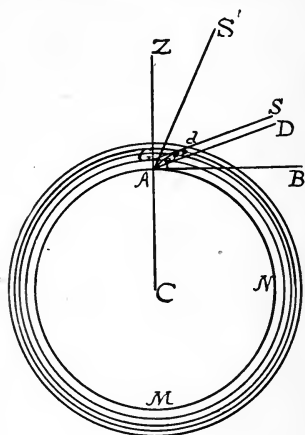
$$\therefore \text{dip in minutes} = 1.063 \sqrt{h}.$$

This value of dip is diminished by refraction. The amount by which it is diminished is variously estimated. If we take that amount as  $\frac{3}{40}$ , we shall obtain the true value of dip; allowing for refraction, dip =  $1.063 \sqrt{h} - \frac{3}{40}(1.063 \sqrt{h}) = .984 \sqrt{h}$ , approximately.



72. *Refraction.* To understand the effect of refraction, we represent, by the figure, a great circle section of the earth  $AMN$ , made by a plane passing through  $A$ , the point of observation, and through the atmosphere surrounding the earth.

A ray of light from a distant object, as a star,  $S$ , entering the atmosphere obliquely at  $d$ , and passing through strata of varying density, is bent out of its course into a curve,  $defgA$ , concave to the earth's surface. The object itself



appears at  $A$  on  $AS'$ , which is a line tangent to the curve  $defgA$  at  $A$ .

If we join the center  $C$  with  $A$  and produce the line to  $z$ ,  $z$  will represent the zenith of the observer. Produce the line  $Sd$  (supposed to be a straight line before it enters the atmosphere at  $d$ ) to meet  $CZ$  at  $G$ . If we draw  $AD$  parallel to  $GS$ ,  $DAB$  would represent the true altitude of  $S$ ;  $DA$  and  $GS$ , representing rays of light from an object so remote as one of the celestial bodies, may be regarded as parallel straight lines.

If there were no refraction, the light would come on the line  $AD$ .  $S'AD$  is the angle of refraction. The correction for refraction, therefore, is to be sub-

tracted from the observed altitude to give the true altitude, for  $S'AB - S'AD = DAB$ .

Rays of light from an object in the *zenith*, falling on the strata of the atmosphere, are not *refracted*.

The more obliquely the light enters the atmosphere, the greater the refraction. Consequently, refraction increases, the nearer the body is to the horizon.

**73. Correction for semidiameter.** The positions of heavenly bodies indicated in the Nautical Almanac are given for their *centers*.

Observations of heavenly bodies of perceptible size are generally made to the upper or lower edge of the body, called respectively the *upper* or *lower limb*.

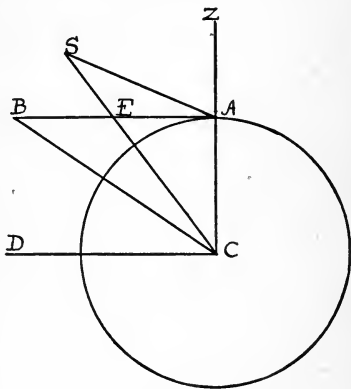
If an observed altitude is one of the *lower limb*, the semi-diameter expressed in minutes or seconds of the body must be *added* to give the altitude of the center. If an observation is taken of the *upper limb*, the semidiameter must be *subtracted* to give the true altitude.

**74. Parallax.** Altitudes of celestial objects are observed at the surface of the earth, or slightly above it. They are taken with reference to the *sensible horizon*, that is, with a *plane tangent to the earth's surface vertically below* the point of observation. But to these observed altitudes we have to apply corrections in order to obtain the altitudes of the same bodies if the observations were made at the center of the earth, and with reference to the *rational horizon*,

that is, a plane passed through the center of the earth parallel to the sensible horizon.

Let the figure represent a section of the earth made by a plane passed through its center  $C$ , and through the point of observation at  $A$ .

Produce line  $CA$  to zenith  $Z$ . Let  $S$  be position of heavenly body. Its altitude with reference to the sensible horizon, represented by line  $AB$  drawn perpendicular to  $AC$ , is the angle  $SAB$ . Its altitude with reference to the rational horizon, represented by line  $CD$ , drawn parallel to  $AB$ , is the angle  $SCD$ .



Let  $E$  be the point where  $AB$  and  $SC$  intersect. Since  $AB$  and  $CD$  are parallel,

$$(1) \quad SCD = SEB = SAB + ASC.$$

The angle  $ASC$  is called the *parallax in altitude* of  $S$ , or simply *parallax* of  $S$ . To obtain the true altitude of a heavenly body (in addition to the other corrections to be applied to the observed altitude), from equation (1) it is evident that parallax must be *added* to the *observed altitude*.

Let  $R$  denote  $AC$ , the radius of the earth; let  $d$  denote  $CS$ , the distance of the heavenly body from

the center of the earth. Denote observed altitude  $SAB$  by  $h$ .

$$\frac{\sin ASC}{\sin SAC} = \frac{R}{d}; \quad \text{that is, } \frac{\sin \text{parallax}}{\sin (90^\circ + h)} = \frac{R}{d};$$

$$\text{or (2) } \sin (\text{parallax}) = \frac{R}{d} \sin (90^\circ + h) = \frac{R}{d} \cos h.$$

Suppose the celestial body to be in the horizon at  $B$ ; then

$$\sin \text{parallax} = \sin ABC = \frac{R}{d}.$$

In this case the parallax is called the *horizontal parallax*; that is,

$$(3) \quad \sin \text{horizontal parallax} = \frac{R}{d}.$$

Substituting in (2) this equivalent of  $\frac{R}{d}$ , we have

$$(4) \quad \sin \text{parallax} = \sin (\text{horizontal parallax}) \cos h.$$

Since parallax and horizontal parallax are always small angles (except in the case of the moon), we may substitute for the sines the measures of these angles, at any altitude, and (4) becomes

$$\text{parallax} = \text{horizontal parallax} \times \cos h.$$

Both from the equation and from the figure it is evident that parallax is *greatest* when the heavenly body is in the *horizon*; *decreases* as the *altitude* of the body *increases*; and vanishes at the *zenith*.

Also, from the figure, if  $S$  be at a very great distance from the earth,  $d$  may be so large that the ratio  $\frac{R}{d}$  approaches 0; in that case, sin parallax in (2) will vanish. For the *fixed stars*, which are supposed to be at such immense distances from the earth that rays of light from them fall on any two points of the earth in nearly parallel lines, no correction for *parallax* is applied.

Again, the nearer  $S$  is to the earth, the greater the value of  $\frac{R}{d}$ , and consequently the greater the parallax. Of the heavenly bodies, the moon is the nearer to the earth and has the greatest parallax.

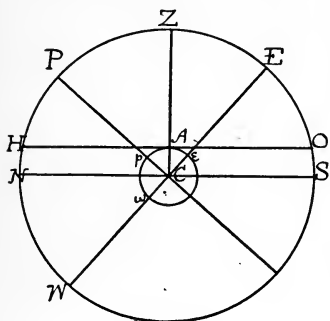
## CHAPTER IX

## LATITUDE

75. *Latitude.*

Let  $wpAe$  represent a great circle section of the earth through the meridian of the observer at  $A$ ; and

let  $NPS$  be the celestial meridian of the same observer.  $wCe$  will then be the projection of the terrestrial equator, and  $WCE$  will be the projection of the celestial equator, or equinoctial on the same plane, viz. the plane of the terrestrial and celestial



meridians. Let  $p$  be the pole of the earth, and  $P$  the corresponding elevated pole of the celestial concave. Join  $CA$ , and produce the line to meet the celestial concave at  $Z$ , the zenith of the observer.

Through  $C$  at right angles to  $CA$  draw  $NCS$ , which will represent the projection of the *rational horizon* of the observer. If at  $A$  a line be drawn tangent to the circle  $pAe$ , cutting the celestial meridian at  $H$  and  $O$ , this line would represent the *sensible horizon* of the observer (Art. 74).

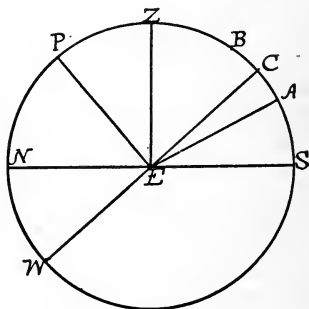
In consequence of the immense distances of the

heavenly bodies on the celestial concave,  $O$  and  $S$  and  $H$  and  $N$  are supposed to coincide, and altitudes of objects are observed with reference to  $HAO$ . Where accuracy is required, such observations have to be *corrected* so as to equal the true altitude with reference to  $NCS$  (Art. 74).

$Ae$  measures the latitude of  $A$ , viz. the angle  $ACe$ . This angle is also measured by  $ZE$ .  $NZ = 90^\circ = PE$ . If from these equals we take away the common part  $PZ$ , we have  $PN = ZE$ ; or, the *elevation* of the nearer *celestial pole* above the horizon of the observer is equal to his *latitude*.

**76.** To find the latitude. Latitude is found by *observing the altitude* of any heavenly body while *on the meridian, the declination* of the body being given.

The altitude of the body may be observed either at its *upper transit* or at its *lower transit*, in case it moves in a small circle on the celestial concave, and always above the horizon. Let  $WPZS$  represent the celestial concave projected on the meridian of the observer;  $P$  will



be the nearer (in this case N.) pole;  $Z$  the zenith;  $WEC$  the projection of the equinoctial;  $NES$  the projection of the horizon.  $ZC$  or  $PN$  will measure the latitude (Art. 75).

Suppose  $A$  to be the position of the heavenly body on the meridian at its *upper transit*.

If the angle  $AES$  is observed, the arc  $AS$ , which measures this angle, is known.  $CA$  is the declination, and in this figure is a S. declination.

$$(a) \text{ lat.} = ZC = ZS - (AS + AC) = 90^\circ - (\text{alt.} + \text{dec.}).$$

If the object observed is at  $B$ , and having a N. declination,  $BS$  is the measure of its altitude, and

$$(b) \text{ lat.} = ZC = 90^\circ - (BS - BC) = 90^\circ - (\text{alt.} - \text{dec.}).$$

The observer is supposed to be in the N. hemisphere, and the latitude required is a N. latitude. In this case, therefore, it is easily seen that when the altitude of a body is taken at its *upper transit*, if the latitude required is N. and the declination is S.,

(a) lat. = the complement of the sum of the altitude and declination; but if the latitude required and declination are both N.,

(b) lat. = complement of the altitude diminished by the declination.

If the observer were in the S. hemisphere, since  $CA$  would then be a N. declination and  $CB$  a S. declination,

$$(c) \text{ lat.} = 90^\circ - (\text{alt.} + \text{dec.}), \text{ if lat. is S. and dec. N.}$$

$$(d) \text{ lat.} = 90^\circ - (\text{alt.} - \text{dec.}), \text{ if lat. is S. and dec. S.}$$

We can bring these four cases under one rule, viz. :



If latitude and declination are of the *same name* (either N. or S.),

$$(e) \text{ the lat.} = 90^\circ - (\text{alt.} - \text{dec.});$$

but, if of different names,

$$(f) \text{ lat.} = 90^\circ - (\text{alt.} + \text{dec.}).$$

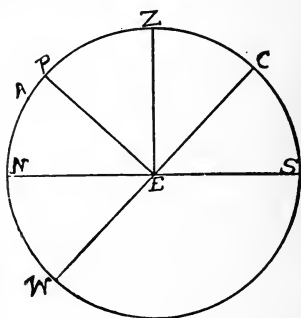
Since the zenith distance of a heavenly body is the complement of its altitude,

$$(g) (e) \text{ becomes lat.} = (90^\circ - \text{alt.} + \text{dec.}) \\ = \text{zenith dist.} + \text{dec.}$$

$$(h) (f) \text{ becomes lat.} = \text{zenith dist.} - \text{dec.}$$

2. Considering now the case of the lower transit of a celestial body,

Let the figure represent, as before, the celestial meridian. Let  $A$  be the position of a heavenly body at its *lower transit*, and  $NA$  the measure of its altitude, and  $WA$  the measure of its declination.



Then  $\text{lat.} = ZC = NP = NA + PA = \text{alt.} + (90 - \text{dec.})$  or  $\text{lat.} = \text{alt.} + \text{polar dist.}$

Ex. 1. June 10, 1895, in long.  $87^\circ 10'$  W., the observed meridian altitude of the sun's lower limb was  $69^\circ 24'$  (zenith N.); the index correction was  $+2' 20''$ ; height of the eye above the sea was 20 ft. Required the latitude.

## Local apparent time

June 10 0 h. 0 m.	obs. alt. = $69^{\circ} 24'$
longitude in time $\underline{5 \text{ h. } 48 \text{ m. } 40 \text{ s.}}$	in. cor. $\underline{2' 20'' +}$
Gr. app. time $\underline{5 \text{ h. } 48 \text{ m. } 40 \text{ s.}}$	$\underline{69^{\circ} 26' 20''}$
= 5.81 h.	dip $\underline{4' 23'' -}$
sun's dec. at app. noon $23^{\circ} 1' 27'' \text{ N.}$	$\underline{69^{\circ} 21' 57''}$
cor. = $11''.5 \times 5.81 = 1' 6''.8 +$	ref. $22'' -$ } $19'' -$
	par. $3'' +$ }
dec. at time of obs. = $\underline{23^{\circ} 2' 33''.8 \text{ N.}}$	$\underline{69^{\circ} 21' 38''}$
5.81	sem. diam. $\underline{15' 47'' +}$
$\underline{11.5}$	true alt. = $\underline{69^{\circ} 37' 25''}$
2905	$\underline{90^{\circ}}$
$\underline{6391}$	zen. dist. $\underline{20^{\circ} 22' 35''}$
66.815 or $1' 6''.8$	dec. $\underline{23^{\circ} 2' 34''}$
	latitude $\underline{43^{\circ} 25' 9'' \text{ N.}}$

In figure, p. 123,  $BS = 69^{\circ} 37' 25''$   
 $BC = 23^{\circ} 2' 34''$   
 $SC = \underline{46^{\circ} 34' 51''}$   
 $90^{\circ} - SC = \text{latitude} = ZC$   
 $= 43^{\circ} 25' 9'' \text{ N.}$

Ex. 2. In long.  $85^{\circ} 14' \text{ W.}$ , Feb. 10, 1897, the observed meridian altitude of the sun's upper limb was  $36^{\circ} 42'$  (zenith N.); index correction was  $-1' 40''$ ; height of eye above sea was 16 ft. Required latitude.

local time 0 h. 0 m.	obs. alt. $36^{\circ} 42'$
longitude in time $\underline{5 \text{ h. } 40 \text{ m. } 56 \text{ s.}}$	in. cor. $\underline{1' 40'' -}$
Gr. app. time $\underline{5 \text{ h. } 40 \text{ m. } 56 \text{ s.}}$	$\underline{36^{\circ} 40' 20''}$
= 5.68 h.	dip $\underline{3' 55'' -}$
sun's dec. at app. noon, $14^{\circ} 9' 32''.6 \text{ S.}$	$\underline{36^{\circ} 36' 25''}$
cor. = $49''.11 \times 5.68 = 4' 38''.9 -$	ref. $1' 18'' -$ } $1' 11'' -$
	par. $7'' +$ }
dec. at time of obs. = $\underline{14^{\circ} 4' 53''.7 \text{ S.}}$	$\underline{36^{\circ} 35' 14''}$
	sem. diam. $\underline{16' 14'' -}$
	true alt. $\underline{36^{\circ} 19'}$

In figure, p. 123,

49.11	$SA = 36^\circ 19'$	
5.68	$CA = 14^\circ 4' 54''$	
39288	$SC = 50^\circ 23' 54''$	90°
29466		true alt. $36^\circ 19'$
24555	$90^\circ - SC = ZC = 39^\circ 36' 6''$	zen. dist. $53^\circ 41'$
278.9448 = 4' 38".9.	latitude = $39^\circ 36' N.$	dec. $14^\circ 4' 54''$
		$39^\circ 36' 6''$

Ex. 3. March 22, 1898, the observed meridian altitude of Arcturus was  $66^\circ 42'$  (zenith N.); index correction was  $2' 20'' +$ ; height of eye 16 ft. Declination of star was  $19^\circ 42' 44'' N.$  Required latitude.

obs altitude	$= 66^\circ 42'$	
index cor.	$= 2' 20'' +$	
	$66^\circ 44' 20''$	
dip	$3' 55'' -$	
	$66^\circ 40' 25''$	
ref. $25'' -$	$25'' -$	
*true alt.	$= 66^\circ 40'$	

In figure, p. 123,

		$SB = 66^\circ 40'$
zen. dist.	$= 23^\circ 20'$	$CB = 19^\circ 42' 44''$
declination	$19^\circ 42' 44''$	$CS = 46^\circ 57' 16''$
	$43^\circ 2' 44''$	latitude = $90^\circ - SC = 43^\circ 2' 44''$
		latitude = $43^\circ 3' N.$

77. To find the latitude by an observation of a heavenly body near the meridian, the declination and the time of the observation being known.

Let *NWSE* represent the projection of the celestial concave on the plane of the horizon; *Z* will be the

\* For fixed star, parallax is 0.



$$(2) \quad \cos AF = \frac{\cos PA}{\cos PF} = \frac{\cos(90^\circ - d)}{\cos x} = \frac{\sin d}{\cos x},$$

$$\cos ZF = \frac{\cos ZA}{\cos AF} = \frac{\cos(90^\circ - a) \cos x}{\sin d};$$

that is, (3)  $\cos y = \sin a \cos x \operatorname{cosec} d.$

By means of (1) we obtain the value of  $x$ , and by means of (3) we obtain  $y$ .

Then latitude =  $90^\circ - (x - y).$

As this method of obtaining latitude depends upon the time (before or after noon), an error in time introduces an error into the result, which is almost unavoidable, so that the method is not very reliable, when the object observed is far from the celestial meridian.\*

Ex. 1. July 15, 1896, in long.  $73^\circ 45'$  W. at 12 h. 45 m. P.M., mean time, the observed altitude of the sun's lower limb was  $58^\circ 42'$  (zenith N. of sun); index correction was  $+2' 20''$ ; height of eye was 15 ft. Required the latitude.

ship time, July 15 = 0 h. 45 m.

longitude = 4 h. 55 m.

Greenwich, July 15,  $M_t = 5$  h. 40 m.

= 5.67 h.

equation of time = 5 m. 46.16 s.

correction  $(.245) \times 5.67 = \frac{1.39}{5 \text{ m. } 47.55 \text{ s.}}$  = equation of time

$\frac{5.67}{1715}$

45 m.

1470

39 m. 12.45 s. = time = apparent time

1225

39 m. =  $9^\circ 45'$

$\frac{1.38915}{38 \text{ m. } 12.45 \text{ s.}}$

12.45 s. =  $3' 7''$

apparent time = 38 m. 12.45 s. =  $9^\circ 48' 7''$

\* Bowditch.

$$\begin{aligned}
 \text{observed altitude} &= 58^\circ 42' \\
 \text{index correction} &= \frac{2' 20'' +}{58^\circ 44' 20''} \\
 \text{dip} &= \frac{3' 48'' -}{58^\circ 40' 32''} \\
 \left. \begin{array}{l} \text{ref. } 35'' - \\ \text{par. } 4'' + \end{array} \right\} &= \frac{31'' -}{58^\circ 40' 01''} \\
 \text{sem. diam.} &= \frac{15' 47'' +}{58^\circ 55' 48''} \\
 \text{true altitude} &= 58^\circ 55' 48'' \\
 &90^\circ \\
 \text{zenith distance} &= 31^\circ 4' 12''
 \end{aligned}$$

declination of sun at noon, Gr. mean time =  $21^\circ 25' 17''.1$  N.

$$\text{correction} = 24''.33 \times 5.67 = \frac{2' 18'' -}{21^\circ 22' 59'' \text{ N.}}$$

declination of sun at time of observation =  $21^\circ 22' 59''$  N.

$$\begin{aligned}
 &90^\circ \\
 \text{polar distance} &= 68^\circ 37' 1''
 \end{aligned}$$

In the preceding figure,

$$\angle APZ = 9^\circ 48' 7''; \quad PA = 68^\circ 37' 1''; \quad ZA = 31^\circ 4' 12''.$$

$$\tan x = \cos 9^\circ 48' 7'' \cot 21^\circ 22' 59''$$

$$\log \cos 9^\circ 48' 7'' = 9.99362$$

$$\log \cot 21^\circ 22' 59'' = 10.40721$$

$$\log \tan 68^\circ 19' 47'' = 10.40083$$

$$x = 68^\circ 19' 47''$$

$$\cos y = \sin 58^\circ 55' 48'' \cos 68^\circ 19' 47'' \operatorname{cosec} 21^\circ 22' 59''$$

$$\log \sin 58^\circ 55' 48'' = 9.93275$$

$$\log \cos 68^\circ 19' 47'' = 9.56734$$

$$\log \operatorname{cosec} 21^\circ 22' 59'' = 10.43818$$

$$\log \cos 29^\circ 49' 51'' = 9.93827$$

$$y = 29^\circ 49' 51''$$

$$x = PF = 68^{\circ} 19' 47''$$

$$y = ZF = 29^{\circ} 49' 51''$$

$$x - y = PZ = 38^{\circ} 29' 56''$$

$$PH = 90^{\circ}$$

$$ZH = \text{lat.} = 51^{\circ} 30' 4'' \text{ N.}$$

Ex. 2. Jan. 16, 1895, at 12 h. 42 m. 30 s. P.M., mean time, in long.  $64^{\circ} 20'$  W., the observed altitude of the sun's lower limb was  $17^{\circ} 50' 20''$  (zenith N.); index correction was  $-2' 10''$ ; height of eye 12 ft. Required the latitude.

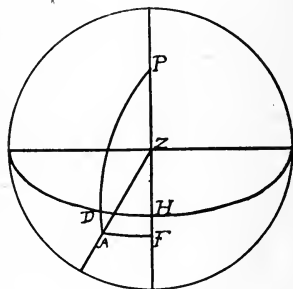
$$\text{ship time} = 0 \text{ h. } 42 \text{ m. } 30 \text{ s.}$$

$$\text{longitude} = 4 \text{ h. } 17 \text{ m. } 20 \text{ s.}$$

$$\text{Greenwich, Jan. 16} = 4 \text{ h. } 59 \text{ m. } 50 \text{ s.}$$

$$= 4.997 \text{ h.}$$

$$= 5 \text{ h. nearly}$$



$$\text{declination of sun Jan. 16, noon} = 20^{\circ} 55' 58'' \text{ S.}$$

$$\text{correction} = 28''.68 \times 5 = 2' 23'' -$$

$$\text{declination of sun at time of observation} = 20^{\circ} 53' 35'' \text{ S.}$$

$$\therefore PA = 110^{\circ} 53' 35''.$$

$$\text{equation of time at noon} = 9 \text{ m. } 58.25 \text{ s.}$$

$$\text{correction} = 0.849 \times 5 = 4.25 \text{ s.}$$

$$\text{equation of time for observation} = 10 \text{ m. } 2.5 \text{ s.}$$

$$\text{mean time} = 42 \text{ m. } 30 \text{ s.}$$

$$\text{apparent time} = 32 \text{ m. } 27.5 \text{ s.}$$

$$= 8^{\circ} 6' 52\frac{1}{2}'' = \angle APF$$

$$\text{observed altitude} = 17^{\circ} 50' 20''$$

$$\text{index correction} = \quad 2' 10''$$

$$\hline 17^{\circ} 48' 10''$$

$$\text{dip} = \quad 3' 24''$$

$$\hline 17^{\circ} 44' 46''$$

$$\left. \begin{array}{l} \text{ref. } 3' - \\ \text{par. } 8'' + \end{array} \right\} = \quad 2' 52''$$

$$\hline 17^{\circ} 41' 54''$$

$$\text{sem. diam.} = \quad 16' 18''$$

$$\text{true altitude} = 17^{\circ} 58' 12''$$

$$\therefore ZA = 72^{\circ} 1' 48''$$

In triangle  $PAF$ ,

$$\tan PF = \tan x = \frac{\cos 8^{\circ} 6' 52'' \frac{1}{2}}{\cot 110^{\circ} 53' 35''}$$

$$\log \cos 8^{\circ} 6' 52'' \frac{1}{2} = 9.99563$$

$$\log \cot 110^{\circ} 53' 35'' = 9.58175$$

$$\log \tan 111^{\circ} 5' 10'' = 10.41388$$

$$\cos AF = \frac{\cos 110^{\circ} 53' 35''}{\cos x}$$

In triangle  $ZAF$ ,

$$\cos ZF = \cos y = \frac{\cos ZA}{\cos AF}$$

or 
$$\cos y = \frac{\cos 72^{\circ} 1' 48''}{\cos 110^{\circ} 53' 35''} \cos 111^{\circ} 5' 10''$$

$$\log \cos 72^{\circ} 1' 48'' = 9.48927$$

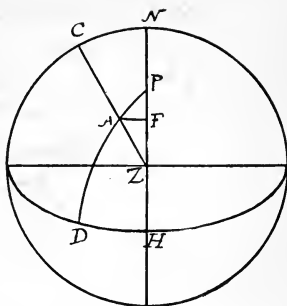
$$\log \cos 111^{\circ} 5' 10'' = 9.55602$$

$$\log \sec 110^{\circ} 53' 35'' = 10.44778$$

$$\log \cos 71^{\circ} 52' 1'' = 9.49307$$



$$\begin{aligned}
 x &= 111^\circ 5' 10'' &= PF \\
 y &= 71^\circ 52' 1'' &= ZF \\
 x - y &= \frac{39^\circ 13' 9''}{90^\circ} &= PZ \\
 \text{lat.} &= 50^\circ 46' 51'' \text{ N.} &= ZH
 \end{aligned}$$



In case the perpendicular meets the meridian at  $F$ , a point between  $P$  and  $Z$ , as in the figure, then  $PZ = x + y$  and  $ZH = \text{lat.} = 90^\circ - (x + y)$ . In this case  $PA = (90 - d)$ .

Ex. 3. If in long.  $60^\circ 10' \text{ W.}$ , on Jan. 3, 1895, at 5 h. 42 m. 13 s. 13 s. P.M., mean time, the declination of a star was found to be  $72^\circ 12' \text{ N.}$ , and its true altitude to be  $58^\circ 42' 40''$  (zenith N.), required the latitude.

ship time, Jan. 3 = 5 h. 42 m. 13 s.

longitude = 4 h. 0 m. 40 s.

Greenwich, Jan. 3. mean time = 9 h. 42 m. 53 s.

R.A. of mean sun 3d noon = 18 h. 51 m. 25.5 s.

Correction for 9 h. 42 m. 53 s. = 1 m. 35.7 s.

R.A. mean sun = 18 h. 53 m. 01 s.

mean time = 5 h. 42 m. 13 s.

24 h. 35 m. 14 s.

24 h.

sidereal time = 0 h. 35 m. 14 s. =  $APZ$ .

$AC = 58^\circ 42' 40''$

$AD = 72^\circ 12'$

$90^\circ$

$PA = 17^\circ 48'$

$AZ = 31^\circ 17' 20''$

$\tan x = \frac{\cos 35 \text{ m. } 14 \text{ s.}}{\cot 17^\circ 48'}$

$\log = 9.99485$

$\log = 10.49341$

$\log \tan 17^\circ 36' 11''$

$= 9.50144$

$$\cos y = \cos 31^\circ 17' 20'' \cos 17^\circ 36' 11'' \sec 17^\circ 48'$$

$$\log \cos 31^\circ 17' 20'' = 9.93174$$

$$\log \cos 17^\circ 36' 11'' = 9.97917$$

$$\log \sec 17^\circ 48' = \underline{10.02130}$$

$$\log \cos 31^\circ 11' 15'' = 9.93221$$

$$PF = 17^\circ 36' 11'' = x$$

$$ZF = 31^\circ 11' 15'' = y$$

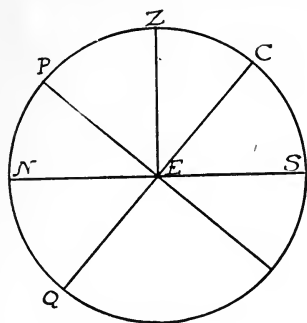
$$PZ = \underline{48^\circ 47' 26'' = x + y}$$

$$90^\circ$$

$$ZH = \text{lat.} = \underline{41^\circ 12' 34'' \text{ N.}} = 90^\circ - (x + y).$$

78. To find the latitude by *observing* the *altitude* of the *Pole Star* (Polaris). This method is confined to northern latitudes.

Let the figure represent the projection of the celestial concave on the celestial meridian; *P* the N. pole;



*Z* the zenith; *QEC* the projection of the equinoctial; *NES* the projection of the horizon.

Since  $PC = 90^\circ$  and  $ZN = 90^\circ$ ,  $PC = ZN$ . If from these equals we take  $PZ$ ,  $PN = ZC$ , but  $ZC =$  the latitude of the observer; that is,  $PN$ , the altitude of

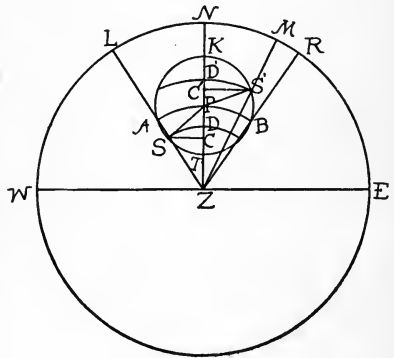
the nearer pole above the horizon, is equal to the latitude (a principle already shown in Art. 75).

The star called Polaris is very near the N. pole of celestial sphere. It moves in a small circle about that pole. The polar distance of this circle is very nearly

$1^{\circ} 14'$  (1898). By observing its altitude, at its upper and lower culminations, and subtracting or adding its exact polar distance, the latitude may be obtained. As this method is not always practicable, its altitude is observed at any moment, and to this altitude corrections are applied which are arranged in tables for the purpose of obtaining the true latitude.

Let the figure represent the projection of the celestial concave on the plane of the horizon. In order to

understand the corrections required, draw  $ASBS'$  to represent the circle in which Polaris moves each 24 hours (sidereal). If, with  $Z$  as a pole and a distance  $ZP$  we describe a circle, cutting  $ASBS'$  in the points  $A$  and  $B$ , these



points will be the points where the altitude of Polaris will be the same as the altitude of  $P$ . Since  $ZL$ ,  $ZN$ , and  $ZR$  each equals  $90^{\circ}$ , and  $ZA = ZP = ZB$ , therefore  $AL = PN = BR$ . If we take any other position of the star, as  $S$ , on the arc  $ASB$ , its altitude will evidently be greater than that of the pole  $P$ , or if we take  $S'$  on the arc  $AS'B$ , its altitude will be *less* than that of the pole  $P$ .

If, with  $Z$  as a pole and polar distance  $ZS$  we describe a circle cutting the meridian  $ZN$  in  $D$ , the

altitude of  $S$  will be the same as that of  $D$ ; and if with polar distance  $ZS'$  we draw a circle cutting meridian at  $D'$ , the altitude of  $S'$  will be the same as that of  $D$ . Join  $PS$  and  $PS'$ , and from  $S$  and  $S'$  draw  $SC$  and  $S'C'$ , perpendiculars to the meridian.

If we denote the hour angle of the star in any position by  $t$ , then at position  $S$  the angle  $SPC$  will be  $t$ , and at  $S'$  the salient angle  $S'PC'$  will be  $t$ . The triangles  $SPC$  and  $S'PC'$  may be considered as plane triangles, since their sides are such small arcs. Consequently,

$$(1) \quad PC = PS \cos SPC = PS \cos t,$$

and 
$$(2) \quad PC' = PS' \cos S'PC' = PS' \cos t.$$

Now,  $PS$  and  $PS'$  are the *polar distances* of the star, and therefore are the *complements of its declination*. As the declination is given in the Nautical Almanac,  $PS$  and  $PS'$  are known. Denote  $PS$  and  $PS'$  by  $p$ ; then  $PC$  and  $PC'$  from equations (1) and (2) can both be expressed by one equation, viz.:

$$PC, \text{ or } PC' = p \cos t.$$

In this expression attention must be paid to the sign of  $\cos t$ . From 0 h. to 6 h. and from 18 h. to 24 h. the sign is +; between 6 h. and 18 h. the sign is -.

From the figure it is evident that for an observed altitude of the star in any position on the arc  $ATB$ , except at the points  $A$ ,  $T$ , and  $B$ , the latitude,

$$\begin{aligned} PN &= ND - DP = ND - (PC - CD) \\ &= \text{altitude} - p \cos t + CD. \end{aligned}$$

At  $A$  and  $B$  the latitude = altitude, since by construction  $ZA$ ,  $ZP$ , and  $ZB$  are equal. At  $T$  the latitude =  $NP = NT - PT = \text{altitude} - p$ .

For star observed in any position on arc  $AKB$ , except  $A$ ,  $K$ , and  $B$ , latitude,

$$PN = ND' + D'P = ND' + (PC' + C'D'),$$

or latitude = altitude +  $p \cos t + C'D'$ .

At  $K$  the latitude =  $PN = NK + PK = \text{altitude} + p$ .

The values of  $p \cos t$  and of  $CD$ , for all positions of Polaris, are calculated and arranged in tables. When the latitude is desired within  $2'$  of the true latitude, the table for  $p \cos t$  is used.\* If, however, the correct latitude is required, the corrections for  $CD$  must also be applied.

The method of using the table for  $p \cos t$ , only, "is sufficiently precise for nautical purposes." †

Ex. April 1, 1898, 10 P.M. (mean time) nearly, in longitude  $72^\circ 56' W.$ , the altitude of Polaris was observed, and, corrected, was found to be  $40^\circ 22'$ . Required the latitude.

	local time = 10 h. 0 m. 0 s.
	longitude = <u>4 h. 51 m. 44 s.</u>
Greenwich, April 1, mean time =	<u>14 h. 51 m. 44 s.</u>
Greenwich, April 1, R.A. mean sun =	0 h. 39 m. 27.9 s.
correction for 14 h. 51 m. 44 s. =	<u>2 m. 26 s.</u>
R.A. M. sun at time of observation =	0 h. 41 m. 54 s.
	local mean time = 10 h.
	<u>local sidereal time = 10 h. 41 m. 54 s.</u>
	R.A. Polaris = <u>1 h. 21 m. 48 s.</u> -
	hour angle = 9 h. 20 m. 06 s.
	for hour angle of 9 h. 20 m.
correction from page 170 is	<u>+ 56'.9</u>
approximate latitude =	<u><math>41^\circ 19' N.</math></u>

\* Martin.

† Bowditch.

## CHAPTER X

## LONGITUDE

79. By Art. 54 the *local time* was defined as the *hour angle* of the sun at the celestial meridian of the place; and the *Greenwich time* at the same instant was defined as the hour angle of the sun at the meridian of Greenwich, both angles being made at the pole by the hour circle passing through the sun with the respective meridians of the place and of Greenwich. The difference of these angles can be expressed either in degree measure or in time measure. Expressed in degree measure, it is called the longitude of the place. The *longitude* of a *place* can always be determined, therefore, by comparing the *local* time with the *Greenwich* time at the same instant.

All sea-going vessels are furnished with a fixed chronometer set to Greenwich time. Its *rate*, or the average amount of time which it loses or gains in a day, is ascertained, and applied to the time indicated.

The *error* of the clock is the amount of time by which it is *fast* or *slow*, as compared with true Greenwich time. Both the rate and error of the clock are kept on record, and taken into account in calculating longitude.

The *local*, or *ship* time, is determined by observing the altitude of some celestial body. When the object observed is not on the meridian of the observer, the latitude of the place of observation, and the declination of the object being known, the hour angle is calculated (Art. 63).

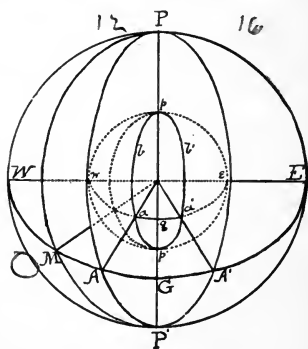
Observations for *latitude* are generally made when the object observed is on *the meridian*, or near it.

Observations for *longitude* are preferred to be taken at the time the object is near the *prime vertical*.

The latitude used in determining the hour angle for longitude is the latitude last observed, corrected for change due to the run of the ship in the interval between the two observations. This change of latitude is found by *dead reckoning*.

80. When the *Greenwich* time is greater than the *ship* time, the *longitude* of the ship is *West*; when the *Greenwich* time is less than the *ship* time, the longitude of the ship is *East*.

Let the figure represent the earth,  $pwp'e$ , and the celestial concave,  $PWP'E$ , projected on the plane at right angles to the meridian of Greenwich.  $pgp'$  will represent the *terrestrial* meridian, and  $PGP'$  the *celestial* meridian of Greenwich. If  $wge$  represent the terrestrial equator, its plane when



produced will intersect the celestial concave in the celestial equator,  $WGE$ .

If  $b$  be a place on the earth's surface west of Greenwich, the plane of its meridian  $pbap'$  produced will intersect the celestial concave in the meridian  $PAP'$ . If  $b'$  be a place east of Greenwich,  $pb'a'p'$  will be its terrestrial meridian, and  $PA'P'$  its celestial meridian.

Now, if the meridian  $PMP'$  be the meridian passing through the mean sun at  $M$ , at the time of an observation,

$GPM$  = Greenwich mean time, at that instant.

$APM$  = mean time at  $b$ , at that instant.

$A'PM$  = mean time at  $b'$ , at that instant.

$GPM - APM = GPA = gpb$ ; because  $GPA$  and  $gpb$  are two arc angles, which are each equal to the diedral angle of the same two planes. But  $gpb$  is measured by  $ga$ , and is the longitude of  $b$  west. Therefore, Greenwich mean time - local mean time = longitude west.

In the same way,  $A'PM - GPM = gpb'$ ; but  $gpb'$  is measured by  $ga'$ , and is the longitude of  $b'$  east. Therefore, local mean time - Greenwich mean time = longitude east.

Ex. 1. At 9.13 P.M. (mean time) nearly, June 24, 1898, in longitude  $16^{\circ} 18'$  W. (by account), a ship's chronometer indicated 10 h. 11 m. 3 s. (Greenwich time). On June 14, at Greenwich mean noon, the chronometer was slow 1 m. 15.8 s., and its mean daily rate was 6.4 s., losing. Required the correct Greenwich mean time, corresponding to ship time.



ship time June 24      9 h. 13 m.  
 longitude              1 h. 5 m. 12 s.  
 Gr. June 24, M. time    10 h. 18 m. 12 s. approximately.

Interval of time between June 14 noon, and 10 h. 18 m. June 24 = 10 d. 10 h. 18 m. = 10 d. 8 h. + 2 h. + 15 m.

daily rate . . . . .	6.4 s.
10 d. . . . .	64.00
8 h. = $\frac{1}{3}$ d. . . . .	2.13
2 h. = $\frac{1}{12}$ d. . . . .	0.53
18 m. = $\frac{1}{80}$ d. . . . .	0.00
	66.7

accum. rate =              1 m. 6.7 s. slow. ∴ to be added.  
 chronometer showed    10 h. 11 m. 3 s.  
                                   10 h. 12 m. 9.7 s.  
 original error              1 m. 15.8 s.  
 cor. Green. mean time = 10 h. 13 m. 25.5 s.

Ex. 2. April 19, 1898, 4 P.M. (mean time) nearly, in latitude 41° 19' N., longitude (by account) 41° 18' W., the altitude of the sun's lower limb was 29° 48' 20", when a chronometer showed 6 h. 49 m. 49 s. The index correction was - 2' 30"; height of eye above sea level, 25 feet. On April 10 at noon, Greenwich mean time, the chronometer was fast 5 m. 10 s., and its daily rate was 2.5 s., gaining. Required the longitude.

ship, April 19	4 h. 0 m. 0 s.	eq. of time	0 m. 57.76 s.
longitude	<u>2 h. 45 m. 12 s.</u>	correction	<u>3.63 s</u>
Green. April 19	6 h. 45 m. 12 s.	eq. of time	1 m. 01.45 s.
	6.75 h.	0.546	<i>to be sub.</i>
		<u>6.75</u>	from ap. time.
		2730	

dec. of sun noon m. t. 11° 16' 44".2 N.    3822  
 correction for 6.75 h.              5' 49".3+    3276  

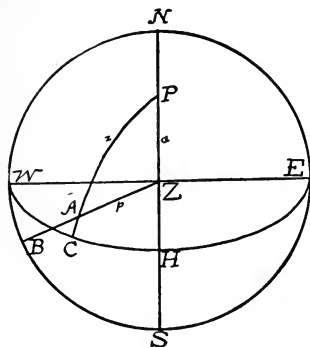

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 declination of sun    11° 22' 33".5 N.    3.6855

51".75	observed altitude of sun	29° 48' 20"
<u>6.75</u>	I. C.	<u>2' 30"-</u>
25875		29° 45' 50"
36225	dip	<u>4' 54"-</u>
<u>31050</u>		29° 40' 56"
349.3125	ref. 1' 42"-	} <u>1' 34"-</u>
	par. 8"+	
5' 49".3	S. D.	<u>15' 57"+</u>
	true altitude	29° 55' 19"

Interval from April 10, noon, to date of observation,  
9 d. 6.75 h.

daily rate . . . . .	2.5 s.	
		<u>9</u>
9 d. . . . .		22.5
$\frac{1}{4}$ d. . . . .		.6
$\frac{1}{3\frac{1}{2}}$ d. . . . .		<u>.1</u>
accum. gain . . . . .		23.2 to be subtracted.
chronometer	6 h. 49 m. 49 s.	
	6 h. 49 m. 26 s.	
original error	<u>5 m. 10 s.</u>	
correct Greenwich time	6 h. 44 m. 16 s.	



$$\begin{aligned}
 PZ &= 90^\circ - 41^\circ 19' = 48^\circ 41' \\
 PA &= 90^\circ - 11^\circ 22' 33''.5 \\
 &= 78^\circ 37' 27'' \\
 AZ &= 90^\circ - 29^\circ 55' 19'' \\
 &= 60^\circ 04' 41'' \\
 a &= 48^\circ 41' \\
 z &= 78^\circ 37' 27'' \\
 p &= 60^\circ 04' 41'' \\
 s &= \underline{187^\circ 23' 8''} \\
 &\quad 2 \\
 &= 93^\circ 41' 34''
 \end{aligned}$$

$$s - a = 45^\circ 0' 34''$$

$$s - z = 15^\circ 04' 7''$$

$$s - p = \underline{33^\circ 36' 53''}$$

$$\sin \frac{1}{2} P = \sqrt{\sin(s - a) \sin(s - z) \operatorname{cosec} a \operatorname{cosec} z}$$

$$\log \sin 45^\circ 0' 34'' = 9.84956$$

$$\log \sin 15^\circ 04' 7'' = 9.41493$$

$$\log \operatorname{cosec} 48^\circ 41' = 10.12432$$

$$\log \operatorname{cosec} 78^\circ 37' 27'' = 10.00862$$

$$2) \underline{19.39743}$$

$$\log \sin \frac{1}{2} (3 \text{ h. } 59 \text{ m. } 44 \text{ s. } + 7 \text{ s.}) = 9.69871\frac{1}{2}$$

$$\underline{53}$$

$$\text{correction } 7 \text{ s.} = \underline{18\frac{1}{2}}$$

$$\text{ship apparent time} = 3 \text{ h. } 59 \text{ m. } 51 \text{ s.}$$

$$\text{equation of time} = \underline{1 \text{ m. } 01 \text{ s.} -}$$

$$\text{ship mean time} = 3 \text{ h. } 58 \text{ m. } 50 \text{ s.}$$

$$\text{Greenwich, mean time} = \underline{6 \text{ h. } 44 \text{ m. } 16 \text{ s.}}$$

$$\text{longitude} = 2 \text{ h. } 45 \text{ m. } 26 \text{ s.}$$

$$= 41^\circ 21' 30'' \text{ W.}$$

Ex. 3. Feb. 13, 1898, 6.30 A.M. (mean time) nearly, in lat.  $45^\circ 16' \text{ S.}$ , and long.  $28^\circ 42' \text{ E.}$  (by account), a chronometer showed 4 h. 41 m. 48 s., when an observed altitude of the sun's upper limb was  $14^\circ 18' 20''$ . Index correction was  $-1' 13''$ , height of eye, 12 ft. Feb. 7, at noon (G.M.T.), the chronometer was slow 3 m. 6 s., and its daily rate was 1.4 s., losing.

$$\text{ship time, Feb. 12} \quad 18 \text{ h. } 30 \text{ m. } 0 \text{ s.}$$

$$\text{longitude} \quad \underline{1 \text{ h. } 54 \text{ m. } 48 \text{ s.}}$$

$$\text{Greenwich, Feb. 12} \quad 16 \text{ h. } 35 \text{ m. } 12 \text{ s.}$$

$$16.59 \text{ h.}$$

$$\text{or Greenwich, Feb. 13} \quad -7.41 \text{ h.}$$

hourly difference of declination	50".65
	<u>7.41</u>
	5065
	20260
	<u>35455</u>
	375".3165, or 6' 15".3

declination of sun, Feb. 13, noon	13° 14' 45" S.
correction for - 7.41 h. =	<u>6' 15"</u>
declination of sun =	13° 21' S.
equation of time, Feb. 13, noon =	14 m. 24.2 s.
correction for - 7.41 h. =	<u>0.6 s.</u>
equation of time =	14 m. 24.8 s. to be added
	to ap. t.

hourly dif. of eq. of time	0.078
	<u>7.41</u>
	78
	312
	<u>526</u>
	.55798

Interval from Feb. 7 noon to time of observation 5 d. 16.59 h.	obs. alt. of sun	14° 18' 20"
	index cor.	<u>1' 13"-</u>
		14° 17' 07"
	dip	<u>3' 24"</u>
daily rate . . . . . 1.4 s.		14° 13' 43"
	ref. 3' 46"-	} 3' 37"
	par. 9"+	
5 d. . . . . <u>7.</u>		14° 10' 06"
½ d. . . . . 0.7		<u>16' 14"</u>
⅙ d. . . . . 0.2	sem. diam.	13° 53' 52"
accumulated loss . . . <u>7.9 s.</u>	true alt. of sun	

chron. showed 4 h. 41 m. 48 s.

4 h. 41 m. 56 s.

orig. error 3 m. 6 s.

cor. G.M.T. 4 h. 45 m. 2 s.

$$\begin{aligned}
 a &= 44^\circ 44' \\
 z &= 76^\circ 39' \\
 p &= 76^\circ 06' 8'' \\
 s &= \frac{197^\circ 29' 8''}{2}
 \end{aligned}$$

$$= 98^\circ 44' 34''$$

$$s - a = 54^\circ 0' 34''$$

$$s - z = 22^\circ 05' 34''$$

$$s - p = 22^\circ 38' 26''$$

$$\tan \frac{1}{2} P = \sqrt{\sin(s - a) \sin(s - z) \operatorname{cosec} s \operatorname{cosec}(s - p)}$$

$$\log \operatorname{cosec} s = 10.00507$$

$$\log \sin(s - a) = 9.90801$$

$$\log \sin(s - z) = 9.57531$$

$$\log \operatorname{cosec}(s - p) = 10.41460$$

$$2) \underline{19.90299}$$

$$\log \tan \frac{1}{2} (6 \text{ h. } 25 \text{ m. } 34 \text{ s.}) \quad 9.95149\frac{1}{2}$$

$$\text{equation of time} \quad \underline{14 \text{ m. } 25 \text{ s.}} \quad \underline{64}$$

$$\text{mean time of ship} \quad 6 \text{ h. } 39 \text{ m. } 59 \text{ s.} \quad \underline{14\frac{1}{2}}$$

$$\text{Greenwich mean time} \quad \underline{4 \text{ h. } 45 \text{ m. } 2 \text{ s.}}$$

$$\text{longitude} \quad 1 \text{ h. } 54 \text{ m. } 57 \text{ s.} = 28^\circ 44' 15'' \text{ E.}$$

Ex. 4. Jan. 20, 1898, 8.30 A.M., (mean time) nearly, latitude  $39^\circ 58'$  N., longitude, by account,  $30^\circ 15'$  W., a chronometer showed 10 h. 53 m. 9 s., when an observed altitude of the sun's upper limb was  $13^\circ 2' 30''$ . Index correction was  $-3' 50''$ , height of eye was 18 ft. Jan. 12, noon, Greenwich mean time, the chronometer was 10 m. 36 s. fast and its daily rate was 1.2 s., gaining. Required the longitude.

ship, Jan. 19 20 h. 30 m. dec. of sun Jan. 20 noon  $20^\circ 3' 9''.8 \text{ S.}$

longitude  $\underline{2 \text{ h. } 1 \text{ m.}}$  correction for  $-1.48$   $\underline{48''.6}$

Gr. Jan. 19 22 h. 31 m. declination of sun  $20^\circ 3' 58''.4 \text{ S.}$

$$= 22.52 \text{ h. or Jan. 20 } - 1.48 \text{ h.}$$

	32".84	
	<u>1.48</u>	
interval from Jan. 12 noon	26272	eq. of time 11 m. 19.98 s.
to time of obs. 7 d. 22½ h.	13136	correction <u>1.07 s.</u>
daily rate 1.2 s.	<u>3284</u>	eq. of time 11 m. 18.91 s.
7	48.6032	0.724 to be added to
7 d. = 8.4		<u>1.48</u>
½ d. = .6		5792
⅓ d. = .4		2896
¼ d. = .1		<u>724</u>
accum. gain 9.5 s.	1.07152	
accum. gain = 9.5 s.		obs. alt. of sun 13° 2' 30"
chron. showed 10 h. 53 m. 9 s.		I.C. <u>3' 50"</u>
<u>10 h. 52 m. 59.5 s.</u>		12° 58' 40"
original error 10 m. 36 s.		dip <u>4' 09"</u>
Gr. M. time 10 h. 42 m. 23.5 s.		12° 54' 31"
$a = 50^\circ 2'$		ref. 4' 9" - } 4' 00" -
$z = 110^\circ 3' 58''$		par. 9" + }
$p = 77^\circ 25' 46''$		<u>12° 50' 31"</u>
$s = 237^\circ 31' 44''$		S.D. <u>16' 17" -</u>
2		true alt. of sun 12° 34' 14" -
= 118° 45' 52"		log cosec = 10.05720
$s - a = 68^\circ 43' 52''$		log sin = 9.96936
$s - z = 8^\circ 41' 54''$		log sin = 9.17966
$s - p = 41^\circ 20' 06''$		log cosec = <u>10.18016</u>
log tan ½ (8 h. 29 m. 52 s. + 3 s.)		2) <u>19.38638</u>
ship apparent time 8 h. 29 m. 55 s.		9.69319
equation of time 11 m. 19 s.		<u>29</u>
<u>8 h. 41 m. 14 s.</u>		3 s. cor. for <u>10</u>

Greenwich mean time = 10 h. 42 m. 23.5 s.

ship mean time      8 h. 41 m. 14 s.

longitude            2 h. 01 m. 9.5 s.

longitude      30° 17' 22½" W.

Ex. 5. April 9, 1898, 4 P.M. (mean time) nearly, in latitude 46° 52' N., longitude (by account), 50° 35' W., a chronometer showed 7 h. 28 m. 4 s., when the altitude of the sun's lower limb was 23° 58' 40". Index correction was + 2' 48"; height of eye above sea level, 14 ft. April 1, noon, Greenwich mean time, the chronometer was slow 6 m. 35 s., and its daily rate was 1.2 s., losing. Required the longitude. *Ans.* 50° 39' W.

Ex. 6. June 13, 1898, 6 P.M. (mean time) nearly, in latitude 42° 4' N., longitude (by account), 36° 22' W., the observed altitude of sun's lower limb was 15° 7' 30", when a chronometer showed 8 h. 16 m. 28 s. Index correction was - 3' 14"; height of eye, 20 ft. June 1, noon, Greenwich mean time, chronometer was slow 8 m. 13 s., and its daily rate was 1.3 s., gaining. Required the longitude. *Ans.* 35° 57' W.

Ex. 7. May 2, 1898, 5 P.M. (mean time) nearly, in lat. 50° 16' N., longitude (by account) 40° 18' W., the observed altitude of the sun's lower limb was 21° 16' 50", when a chronometer showed 7 h. 44 m. 2 s. Index correction was + 1' 12"; height of eye above sea level was 15 ft. April 25, noon, G.M.T., chronometer was fast 6 m. 18 s., and daily rate was 0.6 s., losing. Required the longitude. *Ans.* 40° 16' W.

Ex. 8. May 14, 1898, 6 A.M. (mean time) nearly, in lat. 44° 48' N., longitude (by account) 33° 22' W., the observed altitude of the sun's lower limb was 13° 5' 40", when a chronometer showed 8 h. 23 m. 28 s. Index correction was - 2' 25"; height of eye above sea level was 18 ft. May 6, at noon, G.M.T., the chronometer was fast 12 m. 36 s., and its daily rate was 1.6 s., gaining. Required the longitude. *Ans.* 33° 24¼' W.

Ex. 9. Feb. 28, 1898, 8 A.M. (mean time) nearly, in lat.  $46^{\circ} 22' N.$ , longitude (by account)  $50^{\circ} 42' W.$ , a chronometer showed 11 h. 30 m. 54 s., when the observed altitude of the sun's upper limb was  $14^{\circ} 25' 30''$ . Index correction was  $+2' 20''$ ; height of eye above sea level was 20 ft. Feb. 20, noon, G.M.T., chronometer was slow 4 m. 30 s., and its daily rate was 0.8 s., gaining. Required the longitude.

Given dec. of sun, Feb. 28, Green., noon,  $7^{\circ} 50' 24'' S.$

Hourly dif.  $56''.79 N.$

Equation of time at Green., noon, 12 m. 40.7 s. to be added to mean time. Hourly dif. 0.479 s., decreasing from Feb. 28 to March 1.

*Ans.*  $50^{\circ} 39' 15'' W.$



## DEFINITIONS OF TERMS USED IN NAUTICAL ASTRONOMY

- Altitude.** The altitude of a heavenly body is the angle of elevation of the body above the horizon, and is measured on the circle of altitude passing through the body. This measured *distance* is generally used for the altitude.
- Observed Altitude.** The observed altitude of a heavenly body is the altitude of the body above the sea horizon taken with a sextant or other instrument.
- True Altitude.** The true altitude of a heavenly body is its observed altitude corrected for index error, dip, refraction, parallax, and semi-diameter.
- First Point of Aries.** The first point of Aries is the point on the celestial concave in which the ecliptic cuts the equinoctial, where the sun passes from the south to the north of the equinoctial.
- Axis.** The axis of the celestial sphere is the diameter about which the celestial concave appears to revolve from east to west. It is coincident with the earth's axis produced.
- Azimuth.** The azimuth or true bearing of a heavenly body is the angle at the zenith made by the celestial meridian and the circle of altitude passing through the body.
- Celestial Concave.** The celestial concave is the surface of a very large sphere of which the center is the center of the earth.
- Apparent Solar Day.** An apparent solar day is the interval of time between two successive transits of the sun over the same celestial meridian.

**Mean Solar Day.** A mean solar day is the interval of time between two successive transits of the mean sun over the same celestial meridian.

**Sidereal Day.** A sidereal day is the interval of time between two successive transits of the first point of Aries over the same celestial meridian.

**Declination.** The declination of a heavenly body is the arc of a circle of declination between the body and the equinoctial, or celestial equator.

**Circles of Declination.** Circles of declination are great circles of the celestial concave which pass through its poles. Circles of declination are also called hour circles.

**Angle of Depression.** The angle of depression of any body below the observer is the angle between a line drawn to it from the observer's eye, and the horizontal plane through the observer's eye.

**Ecliptic.** The ecliptic is the great circle in which the plane of the earth's orbit cuts the celestial concave.

**Angle of Elevation.** The angle of elevation of any body above the observer is the angle at the observer's eye, between a line drawn from it to the body and a horizontal plane through the eye.

**Celestial Equator and Equinoctial.** The equinoctial is the celestial equator and is the great circle of the celestial concave made by producing the plane of the terrestrial equator to cut the concave.

**Greenwich Date.** The Greenwich date is the astronomical time at Greenwich, when an observation is taken at any place on the earth.

**Horizon.** The celestial horizon or simply the horizon at any place is the great circle of the celestial concave, in which a plane tangent to the earth at that place meets the concave. This plane is known as the plane of the horizon.

**Rational Horizon.** The rational horizon is a plane passed through the center of the earth parallel to the sensible horizon.

**Sensible Horizon.** The sensible horizon is a plane tangent to the earth at a point vertically below the point of observation.

**Visible Horizon.** The visible horizon is the small circle which bounds the vision of the observer.

**Hour Angle.** The hour angle of any heavenly body is the angle at the pole between the celestial meridian of the observer and the hour circle passing through the body.

**Hour Circles.** Hour circles are circles of declination.

**Celestial Meridian.** The celestial meridian of any place is the great circle in which the plane of the terrestrial meridian cuts the celestial concave.

**Apparent Noon.** Apparent noon is the instant when the center of the real sun is on the celestial meridian.

**Mean Noon.** Mean noon is the instant when the mean sun is on the celestial meridian.

**Poles of the Heavens.** The poles of the heavens are the extremities of the axis of the celestial concave.

**Prime Vertical.** The prime vertical is the circle of altitude, whose plane is at right angles to the plane of the celestial meridian.

**Right Ascension.** The right ascension of a heavenly body is the arc of the equinoctial, or celestial equator, between the first point of Aries and the circle of declination passing through the body. Right ascension is *measured in time eastward* from 0 h. to 24 h.

**Apparent Time.** Apparent time is the hour angle of the real sun.

**Mean Time.** Mean time is the hour angle of the mean sun.

**Equation of Time.** The equation of time is the difference between apparent time and mean time.

**Astronomical Time.** Astronomical time is reckoned in periods of twenty-four hours, each period *beginning at noon*.

**Civil Time.** Civil time is reckoned in two periods of twelve hours, named A.M. and P.M. according as they come before or after noon of the day, which, in this method of reckoning time, *begins at midnight*.

**Zenith.** The zenith is the pole of the celestial horizon directly above the observer.

## EXAMPLES

## CHAPTER III

In the following examples, deviation is to be taken from table on page 56. Find the *true courses*:

Ex. 1. Compass course = N.  $47^{\circ}$  E.; variation =  $9^{\circ}$  W.; leeway =  $0^{\circ}$ . *Ans.* N.  $56^{\circ}$  E.

Ex. 2. Compass course = E. b. N.  $\frac{1}{4}$  N.; variation =  $21^{\circ}$  E.; leeway =  $1\frac{1}{4}$  pt. and wind N. *Ans.* S.E.

Ex. 3. Compass course = S.  $51^{\circ}$  E.; variation =  $18^{\circ}$  E.; leeway = 0. *Ans.* S.  $17^{\circ}$  E.

Ex. 4. Compass course = S.  $\frac{3}{4}$  W.; variation =  $21^{\circ}$  W.; leeway = 1 pt.; wind E.S.E. *Ans.* S.  $\frac{1}{4}$  E.

Ex. 5. Compass course = W. b. S.  $\frac{3}{4}$  S.; variation =  $11^{\circ}$  W.; leeway = 1 pt.; wind S. *Ans.* S.W.  $\frac{3}{4}$  W.

Ex. 6. Compass course = N.N.W.  $\frac{1}{4}$  W.; variation =  $30^{\circ}$  W.; leeway =  $\frac{1}{4}$  pt.; wind W. *Ans.* W.N.W.

Find the *compass course*:

Ex. 7. True course = N.N.E.  $\frac{1}{4}$  E.; variation being  $21^{\circ}$  E. *Ans.* N.  $5^{\circ}$  E.

Ex. 8. True course = N.  $62^{\circ}$  E.; variation being  $11^{\circ}$  W. *Ans.* N.  $54^{\circ}$  E.

Ex. 9. True course = E.  $\frac{3}{4}$  S.; variation being  $12^{\circ}$  W. *Ans.* East.

Ex. 10. True course = S. b. W.  $\frac{1}{4}$  W.; variation being  $19^{\circ}$  E. *Ans.* S.  $10^{\circ}$  E.

Ex. 11. True course = N.W.  $\frac{1}{4}$  W.; variation being  $34^{\circ}$  W. *Ans.* N.  $9^{\circ}$  W.

## CHAPTERS V AND VI

Ex. 1. May 28, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., required mean time of apparent noon, and declination of sun at that time.

*Ans.* Mean time, 11 h. 57 m. 4.15 s. A.M.; dec. of sun,  $21^{\circ} 32' 42''$  N.

Ex. 2. May 28, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., given mean times 10.15 A.M. and 1.45 P.M., required corresponding sidereal times.

*Ans.* 14 h. 39 m. 42 s.; 6 h. 10 m. 17 s.

Ex. 3. May 27, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., given mean times 9.45 A.M. and 1.30 P.M., required corresponding sidereal times.

*Ans.* 2 h. 5 m. 41 s.; 5 h. 51 m. 18 s.

Ex. 4. May 27, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., required the mean time of apparent noon; also declination of sun at that time.

*Ans.* 11 h. 56 m. 57 s. A.M.;  $21^{\circ} 23' 2''$  N.

Ex. 5. March 15, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., given apparent times, 6.30 A.M. and 5 P.M., to find corresponding mean times.

*Ans.* 6.39 A.M.; 5 h. 8 m. 52 s. P.M.

Ex. 6. In long.  $72^{\circ} 55\frac{3}{4}'$  W., March 19, 1898, 10.45 A.M. mean time, required apparent time, sidereal time, and declination of sun.

*Ans.* Apparent time, 10 h. 37 m. 13 s.; sidereal time, 22 h. 33 m. 48 s.; declination of sun,  $0^{\circ} 22' 10''$  S.

## CHAPTER VII

Ex. 1. In lat.  $41^{\circ} 18'$  N., long.  $72^{\circ} 55\frac{3}{4}'$  W., May 2, 1898, 3.19 P.M. apparent time, nearly, the true altitude of the sun was  $40^{\circ} 14'$ ; required its hour angle. *Ans.* 3 h. 18 m. 31 s.

Ex. 2. In lat.  $41^{\circ} 18'$  N., long.  $72^{\circ} 55\frac{3}{4}'$  W., Jan. 10, 1898, 10 A.M. mean time approximately, the true altitude of sun was  $20^{\circ} 40'$ ; required mean time. *Ans.* 10 h. 4 m. 53 s. A.M.

Ex. 3. In lat.  $41^{\circ} 18'$  N., long.  $72^{\circ} 55\frac{3}{4}'$  W., Jan. 10, 1898, 11 A.M. mean time approximately, the true altitude of the sun was  $24^{\circ} 40'$ ; required mean time. *Ans.* 10 h. 56 m. 23 s. A.M.

Ex. 4. April 1, 1898, at 7 P.M. mean time nearly, in long.  $72^{\circ} 55\frac{3}{4}'$  W., the hour angle of  $\alpha$  Orionis was 1 h. 50 m. 56 s., W. of meridian. Required mean time.

*Ans.* 6 h. 59 m. 11 s. P.M.

Ex. 5. Nov. 22, 1898, 7.15 P.M. mean time nearly, in long.  $87^{\circ} 56'$  W., the hour angle of Aldebaran ( $\alpha$  Tauri) was 18 h. 55 m. 15 s. (E. of meridian). Nov. 22, noon Greenwich R.A. mean sun was 16 h. 5 m. 58.42 s. *Ans.* 7 h. 17 m. 14 s. P.M.

Ex. 6. Find at what time Procyon ( $\alpha$  Canis Minoris) passed the meridian of  $72^{\circ} 56'$  W., April 5, 1898.

*Ans.* 6 h. 36 m. 51 s. P.M.

Ex. 7. Find at what time Sirius passed the meridian  $72^{\circ} 55\frac{3}{4}'$  W., April 6, 1898. If the place is in lat.  $41^{\circ} 18'$  N., required also its meridian altitude at transit.

*Ans.* 5 h. 39 m. 45 s. P.M.;  $32^{\circ} 7' 27''$ .

Ex. 8. In lat.  $41^{\circ} 18'$  N., long.  $72^{\circ} 55\frac{3}{4}'$  W., April 6, 1898, find at what time Regulus passed the meridian, and at what altitude.

*Ans.* 9 h. 1 m. 29 s. P.M.;  $61^{\circ} 9' 52''$ .

Ex. 9. In lat.  $41^{\circ} 18'$  N., long.  $72^{\circ} 55\frac{3}{4}'$  W., April 5, 1898, 10 P.M. mean time nearly, the altitude of  $\beta$  Geminorum was  $48^{\circ} 17'$ , and its declination was  $28^{\circ} 16' 19''$  N. Required mean time.

*Ans.* 9 h. 57 m. 33 s. P.M.

## CHAPTER IX

Ex. 1. In long.  $72^{\circ} 55\frac{3}{4}'$  W., April 20, 1898, the observed meridian altitude of the sun's lower limb was  $33^{\circ} 22' 30''$  (zenith N.); index correction was  $-2' 10''$ ; height of eye above sea level was 25 ft. Required the latitude.

*Ans.*  $68^{\circ} 11' 27''$  N.

Ex. 2. April 21, 1898, in long.  $72^{\circ} 55\frac{3}{4}'$  W., the observed meridian altitude of the sun's lower limb was  $56^{\circ} 10' 20''$  (zenith N.); index correction was  $+2' 25''$ ; height of eye was 18 ft. Required the latitude.

*Ans.*  $45^{\circ} 37' 52''$  N.

Ex. 3. Jan. 2, 1898, the observed altitude of Vega ( $\alpha$  Lyrae) (zenith N.) was  $70^{\circ} 2' 30''$ ; index correction was  $+2' 16''$ ; height of eye above sea level was 14 ft. Required the latitude.

*Ans.*  $58^{\circ} 40' 34''$  N.

Ex. 4. April 20, 1898, the observed meridian altitude of Arcturus was  $62^{\circ} 40' 30''$ ; index correction was  $+3' 16''$ ; height of eye above sea level was 20 ft. Required the latitude.

*Ans.*  $47^{\circ} 3' 50''$  N.

Ex. 5. March 14, 1898, at 2 A.M. (nearly), in long.  $45^{\circ} 40'$  W., the observed altitude of Polaris was  $43^{\circ} 16'$ ; index correction was  $-2' 22''$ ; height of eye was 18 ft. Required the latitude.

*Ans.*  $44^{\circ} 22'$  N.

Ex. 6. April 22, 1898, at 3 A.M. (nearly), in long.  $50^{\circ} 10'$  W., the observed altitude of Polaris was  $46^{\circ} 38'$ ; index correction was  $+1' 40''$ ; height of eye was 13 ft. Required the latitude.

*Ans.*  $47^{\circ} 18'$  N.

Ex. 7. In long.  $16^{\circ} 16'$  W., June 16, 1898, 12 h. 12 m. 26 s. P.M. mean time, the observed altitude of the sun's upper limb (zenith N.) was  $61^{\circ} 40' 10''$ ; index correction was  $+2' 25''$ ; height of eye above sea level was 17 ft. Required the latitude.

*Ans.*  $51^{\circ} 54' 34''$  N.



**ASTRONOMICAL EPHEMERIS**

**FOR THE**

**MERIDIAN OF GREENWICH**

JANUARY, 1898

I.

AT GREENWICH APPARENT NOON

Day of the Week	Day of the Month	THE SUN'S			Equation of Time, to be Added to Apparent Time	Diff. for 1 hour
		Apparent Declination	Diff. for 1 hour	Semi-diameter		
Sat.	1	S. 22 59 1.6	+12.81	16 18.37	m. s. 3 55.32	s. 1.177
SUN.	2	22 53 40.7	13.94	16 18.37	4 23.36	1.160
Mon.	3	22 47 52.4	15.07	16 18.37	4 51.02	1.143
Tues.	4	22 41 37.1	+16.20	16 18.36	5 18.26	1.126
Wed.	5	22 34 51.8	17.32	16 18.35	5 45.08	1.108
Thur.	6	22 27 45.7	18.43	16 18.33	6 11.42	1.088
Frid.	7	22 20 10.2	+19.53	16 18.30	6 37.29	1.067
Sat.	8	22 12 8.3	20.62	16 18.26	7 2.64	1.045
SUN.	9	22 3 40.3	21.71	16 18.22	7 27.47	1.023
Mon.	10	21 54 46.4	+22.78	16 18.18	7 51.74	1.000
Tues.	11	21 45 26.9	23.84	16 18.13	8 15.46	0.975
Wed.	12	21 35 42.0	24.89	16 18.07	8 38.57	0.950
Thur.	13	21 25 32.0	+25.93	16 18.00	9 1.08	0.925
Frid.	14	21 14 57.1	26.96	16 17.93	9 22.96	0.899
Sat.	15	21 3 57.7	27.98	16 17.86	9 44.21	0.871
SUN.	16	20 52 34.1	+28.98	16 17.78	10 4.79	0.842
Mon.	17	20 40 46.5	29.97	16 17.70	10 24.69	0.814
Tues.	18	20 28 35.3	30.95	16 17.61	10 43.89	0.785
Wed.	19	20 16 0.9	+31.91	16 17.52	11 2.38	0.755
Thur.	20	20 3 3.6	32.86	16 17.42	11 20.12	0.724
Frid.	21	19 49 43.7	33.79	16 17.32	11 37.11	0.693
Sat.	22	19 36 1.6	+34.71	16 17.22	11 53.36	0.661
SUN.	23	19 21 57.8	35.61	16 17.11	12 8.82	0.628
Mon.	24	19 7 32.6	36.49	16 17.00	12 23.47	0.595
Tues.	25	18 52 46.4	+37.35	16 16.89	12 37.34	0.561
Wed.	26	18 37 39.6	38.20	16 16.77	12 50.37	0.526
Thur.	27	18 22 12.6	39.04	16 16.65	13 2.59	0.492
Frid.	28	18 6 25.8	+39.85	16 16.53	13 13.97	0.457
Sat.	29	17 50 19.7	40.65	16 16.40	13 24.53	0.422
SUN.	30	17 33 54.6	41.43	16 16.27	13 34.23	0.387
Mon.	31	17 17 10.9	42.20	16 16.13	13 43.10	0.352
Tues.	32	S. 17 0 9.0	+42.95	16 15.99	13 51.12	0.318

## II.

JANUARY, 1898

AT GREENWICH MEAN NOON

Day of the Week	Day of the Month	THE SUN'S		Equation of Time, to be Subtracted from Mean Time	Diff. for 1 hour	Sidereal Time, or Right Ascension of Mean Sun
		Apparent Declination	Diff. for 1 hour			
		° ' "	"	m. s.	s.	h. m. s.
Sat.	1	S. 22 59 2.4	+12.79	3 55.24	1.176	18 44 37.92
SUN.	2	22 53 41.7	13.93	4 23.27	1.160	18 48 34.48
Mon.	3	22 47 53.7	15.07	4 50.92	1.143	18 52 31.04
Tues.	4	22 41 38.5	+16.20	5 18.16	1.126	18 56 27.60
Wed.	5	22 34 56.4	17.31	5 44.97	1.108	19 0 24.15
Thur.	6	22 27 47.7	18.42	6 11.31	1.088	19 4 20.71
Frid.	7	22 20 12.4	+19.52	6 37.17	1.067	19 8 17.27
Sat.	8	22 12 10.7	20.61	7 2.52	1.045	19 12 13.83
SUN.	9	22 3 43.0	21.69	7 27.34	1.023	19 16 10.39
Mon.	10	21 54 49.4	+22.76	7 51.61	1.000	19 20 6.95
Tues.	11	21 45 30.2	23.83	8 15.32	0.975	19 24 3.50
Wed.	12	21 35 45.6	24.88	8 38.43	0.950	19 28 0.06
Thur.	13	21 25 35.9	+25.92	9 0.94	0.925	19 31 56.62
Frid.	14	21 15 1.4	26.95	9 22.82	0.909	19 35 53.18
Sat.	15	21 4 2.3	27.97	9 44.07	0.871	19 39 49.73
SUN.	16	20 52 39.0	+28.97	10 4.65	0.843	19 43 46.29
Mon.	17	20 40 51.8	29.96	10 24.55	0.814	19 47 42.85
Tues.	18	20 28 40.9	30.94	10 43.75	0.785	19 51 39.40
Wed.	19	20 16 6.8	+31.90	11 2.24	0.755	19 55 35.96
Thur.	20	20 3 9.8	32.84	11 19.98	0.724	19 59 32.52
Frid.	21	19 49 50.3	33.77	11 36.98	0.693	20 3 29.08
Sat.	22	19 36 8.6	+34.69	11 53.23	0.661	20 7 25.63
SUN.	23	19 22 5.1	35.59	12 8.69	0.628	20 11 22.19
Mon.	24	19 7 40.2	36.47	12 23.35	0.595	20 15 18.75
Tues.	25	18 52 54.3	+37.34	12 37.22	0.561	20 19 15.30
Wed.	26	18 37 47.8	38.19	12 50.26	0.526	20 23 11.86
Thur.	27	18 22 21.1	39.02	13 2.48	0.492	20 27 8.42
Frid.	28	18 6 34.7	+39.84	13 13.87	0.457	20 31 4.97
Sat.	29	17 50 28.8	40.64	13 24.43	0.422	20 35 1.53
SUN.	30	17 34 4.0	41.42	13 34.14	0.387	20 38 58.09
Mon.	31	17 17 20.6	42.19	13 43.02	0.352	20 42 54.64
Tues.	32	S. 17 0 19.0	+42.94	13 51.05	0.318	20 46 51.20

MARCH, 1898

I.

AT GREENWICH APPARENT NOON

Day of the Week	Day of the Month	THE SUN'S			Equation of Time, to be Added to Apparent Time	Diff. for 1 hour
		Apparent Declination	Diff. for 1 hour	Semi-diameter		
		° ' "	"	' "	m. s.	s.
Tues.	1	S. 7 27 25.8	+57.05	16 10.36	12 28.85	0.501
Wed.	2	7 4 33.4	57.30	16 10.12	12 16.55	0.522
Thur.	3	6 41 35.2	57.54	16 9.88	12 3.78	0.542
Frid.	4	6 18 31.4	+57.76	16 9.64	11 50.52	0.561
Sat.	5	5 55 22.6	57.97	16 9.39	11 36.80	0.580
SUN.	6	5 32 8.9	58.16	16 9.14	11 22.65	0.598
Mon.	7	5 8 50.8	+58.34	16 8.88	11 8.09	0.615
Tues.	8	4 45 28.7	58.50	16 8.62	10 53.11	0.631
Wed.	9	4 22 2.9	58.65	16 8.36	10 37.79	0.645
Thur.	10	3 58 33.7	+58.78	16 8.10	10 22.14	0.659
Frid.	11	3 35 1.5	58.90	16 7.84	10 6.14	0.672
Sat.	12	3 11 26.7	59.00	16 7.57	9 49.86	0.684
SUN.	13	2 47 49.6	+59.09	16 7.30	9 33.30	0.695
Mon.	14	2 24 10.5	59.16	16 7.03	9 16.48	0.705
Tues.	15	2 0 29.9	59.22	16 6.75	8 59.44	0.714
Wed.	16	1 36 48.2	+59.26	16 6.48	8 42.19	0.722
Thur.	17	1 13 5.6	59.28	16 6.20	8 24.76	0.730
Frid.	18	0 49 22.7	59.29	16 5.92	8 7.13	0.737
Sat.	19	0 25 39.7	+59.28	16 5.64	7 49.37	0.743
SUN.	20	S. 0 1 57.0	59.26	16 5.36	7 31.46	0.749
Mon.	21	N. 0 21 44.8	59.22	16 5.09	7 13.44	0.753
Tues.	22	0 45 25.6	+59.17	16 4.81	6 55.32	0.756
Wed.	23	1 9 4.8	59.10	16 4.54	6 37.13	0.759
Thur.	24	1 32 42.2	59.01	16 4.26	6 18.85	0.762
Frid.	25	1 56 17.2	+58.91	16 3.99	6 0.53	0.764
Sat.	26	2 19 49.6	58.79	16 3.72	5 42.19	0.765
SUN.	27	2 43 18.9	58.65	16 3.45	5 23.81	0.766
Mon.	28	3 6 44.8	+58.50	16 3.18	5 5.44	0.765
Tues.	29	3 30 7.0	58.34	16 2.91	4 47.10	0.763
Wed.	30	3 53 25.1	58.16	16 2.64	4 28.78	0.762
Thur.	31	4 16 38.8	57.97	16 2.37	4 10.54	0.760
Frid.	32	N. 4 39 47.7	+57.77	16 2.10	3 52.37	0.756

## II.

MARCH, 1898

AT GREENWICH MEAN NOON

Day of the Week	Day of the Month	THE SUN'S		Equation of Time, to be Subtracted from Mean Time	Diff. for 1 hour	Sidereal Time, or Right Ascension of Mean Sun
		Apparent Declination	Diff. for 1 hour			
		° ' "	"	m. s.	s.	h. m. s.
Tues.	1	S. 7 27 37.7	+57.06	12 28.95	0.501	22 37 14.73
Wed.	2	7 4 45.2	57.31	12 16.66	0.522	22 41 11.29
Thur.	3	6 41 46.8	57.55	12 3.89	0.542	22 45 7.84
Frid.	4	6 18 42.9	+57.77	11 50.63	0.561	22 49 4.39
Sat.	5	5 55 33.8	57.98	11 36.91	0.580	22 53 0.95
SUN.	6	5 32 20.0	58.17	11 22.76	0.598	22 56 57.50
Mon.	7	5 9 1.7	+58.35	11 8.20	0.615	23 0 54.05
Tues.	8	4 45 39.4	58.51	10 53.23	0.631	23 4 50.61
Wed.	9	4 22 13.3	58.66	10 37.91	0.645	23 8 47.16
Thur.	10	3 58 43.9	+58.79	10 22.25	0.659	23 12 43.71
Frid.	11	3 35 11.5	58.91	10 6.25	0.672	23 16 40.27
Sat.	12	3 11 36.4	59.01	9 49.97	0.684	23 20 36.82
SUN.	13	2 47 59.0	+59.10	9 33.41	0.695	23 24 33.37
Mon.	14	2 24 19.7	59.17	9 16.59	0.705	23 28 29.93
Tues.	15	2 0 38.9	59.23	8 59.55	0.714	23 32 26.48
Wed.	16	1 36 56.8	+59.27	8 42.30	0.722	23 36 23.03
Thur.	17	1 13 14.0	59.29	8 24.86	0.730	23 40 19.58
Frid.	18	0 49 30.8	59.30	8 7.23	0.737	23 44 16.14
Sat.	19	0 25 47.4	+59.30	7 49.47	0.743	23 48 12.69
SUN.	20	S. 0 2 4.5	59.28	7 31.56	0.749	23 52 9.24
Mon.	21	N. 0 21 37.7	59.24	7 13.53	0.753	23 56 5.80
Tues.	22	0 45 18.7	+59.18	6 55.41	0.756	0 0 2.35
Wed.	23	1 8 58.3	59.11	6 37.21	0.759	0 3 58.90
Thur.	24	1 32 35.9	59.02	6 18.93	0.762	0 7 55.46
Frid.	25	1 56 11.3	+58.92	6 0.61	0.764	0 11 52.01
Sat.	26	2 19 44.0	58.80	5 42.26	0.765	0 15 48.56
SUN.	27	2 43 13.6	58.66	5 23.88	0.766	0 19 45.12
Mon.	28	3 6 39.9	+58.51	5 5.51	0.765	0 23 41.67
Tues.	29	3 30 2.4	58.35	4 47.16	0.763	0 27 38.22
Wed.	30	3 53 20.8	58.17	4 28.84	0.762	0 31 34.78
Thur.	31	4 16 34.8	57.98	4 10.59	0.760	0 35 31.33
Frid.	32	N. 4 39 44.0	+57.78	3 52.42	0.756	0 39 27.88

APRIL, 1898

I.

## AT GREENWICH APPARENT NOON

Day of the Week.	Day of the Month	THE SUN'S			Equation of Time, to be Added to		Diff. for 1 hour
		Apparent Declination	Diff. for 1 hour	Semi-diameter	Subtracted from Apparent Time		
		° ' "	"	' "	m. s.	s.	
Frid.	1	N. 4 39 47.7	+57.77	16 2.10	3 52.37	0.756	
Sat.	2	5 2 51.5	57.55	16 1.82	3 34.29	0.751	
SUN.	3	5 25 49.9	57.31	16 1.55	3 16.33	0.745	
Mon.	4	5 48 42.5	+57.06	16 1.28	2 58.52	0.739	
Tues.	5	6 11 29.1	56.81	16 1.01	2 40.86	0.731	
Wed.	6	6 34 9.3	56.54	16 0.73	2 23.39	0.723	
Thur.	7	6 56 42.8	+56.25	16 0.46	2 6.14	0.714	
Frid.	8	7 19 9.3	55.95	16 0.18	1 49.09	0.705	
Sat.	9	7 41 28.4	55.64	15 59.90	1 32.30	0.694	
SUN.	10	8 3 39.9	+55.31	15 59.62	1 15.79	0.682	
Mon.	11	8 25 43.4	54.97	15 59.34	0 59.56	0.669	
Tues.	12	8 47 38.7	54.62	15 59.07	0 43.64	0.656	
Wed.	13	9 9 25.2	+54.25	15 58.79	0 28.06	0.642	
Thur.	14	9 31 2.8	53.87	15 58.52	0 12.81	0.628	
Frid.	15	9 52 31.0	53.47	15 58.25	0 2.08	0.612	
Sat.	16	10 13 49.5	+53.06	15 57.98	0 16.60	0.596	
SUN.	17	10 34 53.0	52.64	15 57.71	0 30.71	0.580	
Mon.	18	10 55 56.0	52.20	15 57.44	0 44.44	0.563	
Tues.	19	11 16 43.4	+51.74	15 57.18	0 57.75	0.546	
Wed.	20	11 37 19.6	51.27	15 56.92	1 10.64	0.528	
Thur.	21	11 57 44.4	50.79	15 56.66	1 23.11	0.510	
Frid.	22	12 17 57.3	+50.29	15 56.40	1 35.12	0.491	
Sat.	23	12 37 58.1	49.77	15 56.15	1 46.70	0.472	
SUN.	24	12 57 46.4	49.24	15 55.90	1 57.80	0.453	
Mon.	25	13 17 21.8	+48.70	15 55.65	2 8.45	0.434	
Tues.	26	13 36 44.1	48.15	15 55.41	2 18.63	0.414	
Wed.	27	13 55 52.9	47.58	15 55.17	2 28.33	0.394	
Thur.	28	14 14 47.8	+47.00	15 54.93	2 37.53	0.373	
Frid.	29	14 33 28.7	46.40	15 54.70	2 46.24	0.352	
Sat.	30	14 51 55.1	45.79	15 54.47	2 54.44	0.331	
SUN.	31	N. 15 10 6.8	+45.18	15 54.24	3 2.13	0.310	

## II.

APRIL, 1898

AT GREENWICH MEAN NOON

Day of the Week	Day of the Month	THE SUN'S		Equation of Time to be Subtracted from		Diff. for 1 hour	Sidereal Time, or Right Ascension of Mean Sun
		Apparent Declination	Diff. for 1 hour	Added to Mean Time			
Frid.	1	N. 4 39 44.0	+57.78	m. s. 3 52.42	s. 0.756	0 39 27.88	
Sat.	2	5 2 48.1	57.56	3 34.33	0.751	0 43 24.44	
SUN.	3	5 25 46.8	57.33	3 16.37	0.745	0 47 20.99	
Mon.	4	5 48 39.7	+57.08	2 58.56	0.739	0 51 17.54	
Tues.	5	6 11 26.6	56.82	2 40.89	0.731	0 55 14.10	
Wed.	6	6 34 7.0	56.55	2 23.42	0.723	0 59 10.65	
Thur.	7	6 56 40.8	+56.26	2 6.16	0.714	1 3 7.20	
Frid.	8	7 19 7.6	55.96	1 49.11	0.705	1 7 3.76	
Sat.	9	7 41 27.0	55.65	1 32.32	0.694	1 11 0.31	
SUN.	10	8 3 38.8	+55.32	1 15.81	0.682	1 14 56.86	
Mon.	11	8 25 42.5	54.98	0 59.57	0.669	1 18 53.42	
Tues.	12	8 47 38.0	54.63	0 43.65	0.656	1 22 49.97	
Wed.	13	9 9 24.8	+54.26	0 28.07	0.642	1 26 46.52	
Thur.	14	9 31 2.6	53.88	0 12.81	0.628	1 30 43.08	
Frid.	15	9 52 31.0	53.48	0 2.08	0.612	1 34 39.63	
Sat.	16	10 13 49.7	+53.07	0 16.60	0.596	1 38 36.19	
SUN.	17	10 34 58.4	52.64	0 30.72	0.580	1 42 32.74	
Mon.	18	10 55 56.7	52.20	0 44.45	0.563	1 46 29.30	
Tues.	19	11 16 44.2	+51.75	0 57.76	0.546	1 50 25.85	
Wed.	20	11 37 20.6	51.28	1 10.65	0.528	1 54 22.40	
Thur.	21	11 57 45.5	50.79	1 23.12	0.510	1 58 18.96	
Frid.	22	12 17 58.6	+50.29	1 35.13	0.491	2 2 15.51	
Sat.	23	12 37 59.6	49.78	1 46.71	0.472	2 6 12.07	
SUN.	24	12 57 48.0	49.25	1 57.82	0.453	2 10 8.62	
Mon.	25	13 17 23.6	+48.71	2 8.47	0.434	2 14 5.18	
Tues.	26	13 36 46.0	48.15	2 18.65	0.414	2 18 1.73	
Wed.	27	13 55 54.9	47.58	2 28.35	0.394	2 21 58.29	
Thur.	28	14 14 49.9	+47.00	2 37.55	0.373	2 25 54.84	
Frid.	29	14 33 30.9	46.41	2 46.26	0.352	2 29 51.40	
Sat.	30	14 51 57.4	45.80	2 54.46	0.331	2 33 47.95	
SUN.	31	N. 15 10 9.1	+45.18	3 2.15	0.310	2 37 44.51	

MAY, 1898

I.

## AT GREENWICH APPARENT NOON

Day of the Week	Day of the Month	THE SUN'S			Equation of Time, to be Subtracted from Apparent Time	Diff. for 1 hour
		Apparent Declination	Diff. for 1 hour	Semi-diameter		
<i>SUN.</i>	1	N. 15 10 6.8	+45.18	15 54.24	m. s. 3 2.13	s. 0.310
Mon.	2	15 28 3.4	44.55	15 54.01	3 9.29	0.288
Tues.	3	15 45 44.7	43.90	15 53.78	3 15.93	0.265
Wed.	4	16 3 10.4	+43.24	15 53.55	3 22.03	0.242
Thur.	5	16 20 20.2	42.57	15 53.32	3 27.56	0.219
Frid.	6	16 37 13.7	41.89	15 53.10	3 32.54	0.195
Sat.	7	16 53 50.8	+41.19	15 52.87	3 36.94	0.172
<i>SUN.</i>	8	17 10 11.0	40.48	15 52.65	3 40.78	0.148
Mon.	9	17 26 14.2	39.77	15 52.43	3 44.03	0.124
Tues.	10	17 42 0.0	+39.04	15 52.21	3 46.70	0.099
Wed.	11	17 57 28.2	38.30	15 51.99	3 48.78	0.075
Thur.	12	18 12 38.3	37.55	15 51.78	3 50.26	0.050
Frid.	13	18 27 30.2	+36.78	15 51.57	3 51.16	0.025
Sat.	14	18 42 3.6	36.00	15 51.37	3 51.46	0.000
<i>SUN.</i>	15	18 56 18.1	35.21	15 51.16	3 51.15	0.025
Mon.	16	19 10 13.4	+34.41	15 50.96	3 50.28	0.049
Tues.	17	19 23 49.4	33.59	15 50.76	3 48.82	0.073
Wed.	18	19 37 5.6	32.76	15 50.57	3 46.79	0.096
Thur.	19	19 50 1.8	+31.92	15 50.38	3 44.19	0.120
Frid.	20	20 2 37.8	31.07	15 50.20	3 41.05	0.143
Sat.	21	20 14 53.2	30.21	15 50.02	3 37.34	0.165
<i>SUN.</i>	22	20 26 47.9	+29.34	15 49.85	3 33.12	0.187
Mon.	23	20 38 21.5	28.46	15 49.68	3 28.38	0.208
Tues.	24	20 49 33.8	27.57	15 49.52	3 23.12	0.229
Wed.	25	21 0 24.7	+26.67	15 49.36	3 17.37	0.249
Thur.	26	21 10 53.8	25.76	15 49.20	3 11.16	0.269
Frid.	27	21 21 1.0	24.84	15 49.05	3 4.48	0.288
Sat.	28	21 30 46.0	+23.91	15 48.91	2 57.34	0.306
<i>SUN.</i>	29	21 40 8.6	22.98	15 48.77	2 49.77	0.324
Mon.	30	21 49 8.8	22.04	15 48.63	2 41.77	0.342
Tues.	31	21 57 46.2	21.08	15 48.49	2 33.36	0.359
Wed.	32	N. 22 6 0.7	+20.12	15 48.36	2 24.55	0.375



## II.

MAY, 1898

AT GREENWICH MEAN NOON

Day of the Week	Day of the Month	THE SUN'S		Equation of Time, to be Added to Mean Time	Diff. for 1 hour	Sidereal Time, or Right Ascension of Mean Sun
		Apparent Declination	Diff. for 1 hour			
		° ' "	"	m. s.	s.	h. m. s.
<i>SUN.</i>	1	N. 15 10 9.1	+45.18	3 2.15	0.310	2 37 44.51
Mon.	2	15 28 5.8	44.54	3 9.31	0.288	2 41 41.06
Tues.	3	15 45 47.1	43.89	3 15.94	0.265	2 45 37.62
Wed.	4	16 3 12.8	+43.24	3 22.04	0.242	2 49 34.18
Thur.	5	16 20 22.6	42.57	3 27.57	0.219	2 53 20.73
Frid.	6	16 37 16.2	41.89	3 32.55	0.196	2 57 27.29
Sat.	7	16 53 53.3	+41.20	3 36.95	0.172	3 1 23.84
<i>SUN.</i>	8	17 10 13.5	40.49	3 40.79	0.148	3 5 20.40
Mon.	9	17 26 16.7	39.77	3 44.04	0.124	3 9 16.95
Tues.	10	17 42 2.5	+39.04	3 46.71	0.099	3 13 13.51
Wed.	11	17 57 30.6	38.30	3 48.79	0.075	3 17 10.07
Thur.	12	18 12 40.8	37.54	3 50.26	0.050	3 21 6.62
Frid.	13	18 27 32.6	+36.77	3 51.16	0.025	3 25 3.18
Sat.	14	18 42 5.9	35.99	3 51.46	0.000	3 28 59.74
<i>SUN.</i>	15	18 56 20.4	35.20	3 51.15	0.025	3 32 56.29
Mon.	16	19 10 15.7	+34.40	3 50.28	0.049	3 36 52.85
Tues.	17	19 23 51.6	33.59	3 48.81	0.073	3 40 49.40
Wed.	18	19 37 7.7	32.76	3 46.78	0.096	3 44 45.96
Thur.	19	19 50 3.8	+31.92	3 44.18	0.120	3 48 42.52
Frid.	20	20 2 39.7	31.07	3 41.04	0.143	3 52 39.08
Sat.	21	20 14 55.1	30.21	3 37.33	0.165	3 56 35.63
<i>SUN.</i>	22	20 26 49.6	+29.34	3 33.11	0.187	4 0 32.19
Mon.	23	20 38 23.2	28.46	3 28.37	0.208	4 4 28.75
Tues.	24	20 49 35.4	27.56	3 23.11	0.229	4 8 25.30
Wed.	25	21 0 26.2	+26.66	3 17.36	0.249	4 12 21.86
Thur.	26	21 10 55.2	25.75	3 11.14	0.269	4 16 18.42
Frid.	27	21 21 2.3	24.83	3 4.46	0.288	4 20 14.98
Sat.	28	21 30 47.2	+23.91	2 57.32	0.306	4 24 11.53
<i>SUN.</i>	29	21 40 9.8	22.98	2 49.75	0.324	4 28 8.09
Mon.	30	21 49 9.8	22.03	2 41.75	0.342	4 32 4.65
Tues.	31	21 57 47.1	21.08	2 33.34	0.359	4 36 1.21
Wed.	32	N. 22 6 1.6	+20.12	2 24.53	0.375	4 39 57.76

JUNE, 1898

I.

AT GREENWICH APPARENT NOON

Day of the Week	Day of the Month	THE SUN'S			Equation of Time, to be Subtracted from	Diff. for 1 hour
		Apparent Declination	Diff. for 1 hour	Semi-diameter	Added to Apparent Time	
		° ' "	"	' "	m. s.	s.
Wed.	1	N. 22 6 0.7	+20.12	15 48.36	2 24.55	0.375
Thur.	2	22 13 52.2	19.16	15 48.23	2 15.36	0.390
Frid.	3	22 21 20.4	18.19	15 48.11	2 5.80	0.405
Sat.	4	22 28 25.3	+17.21	15 47.98	1 55.87	0.420
SUN.	5	22 35 6.6	16.23	15 47.86	1 45.59	0.435
Mon.	6	22 41 24.3	15.24	15 47.74	1 35.00	0.448
Tues.	7	22 47 18.1	+14.24	15.47.62	1 24.09	0.461
Wed.	8	22 52 48.0	13.24	15 47.51	1 12.88	0.473
Thur.	9	22 57 53.8	12.24	15 47.40	1 1.39	0.485
Frid.	10	23 2 35.3	+11.23	15 47.29	0 49.62	0.495
Sat.	11	23 6 52.6	10.21	15 47.19	0 37.63	0.504
SUN.	12	23 10 45.5	9.19	15 47.09	0 25.41	0.513
Mon.	13	23 14 13.8	+ 8.17	15 47.00	0 12.98	0.521
Tues.	14	23 17 17.6	7.14	15 46.91	0 0.38	0.528
Wed.	15	23 19 56.7	6.11	15 46.82	0 12.37	0.534
Thur.	16	23 22 11.0	+ 5.08	15 46.74	0 25.26	0.538
Frid.	17	23 24 0.6	4.05	15 46.67	0 38.25	0.542
Sat.	18	23 25 25.4	3.02	15 46.60	0 51.29	0.545
SUN.	19	23 26 25.4	+ 1.99	15 46.54	1 4.39	0.546
Mon.	20	23 27 0.6	+ 0.95	15 46.48	1 17.50	0.546
Tues.	21	23 27 10.9	- 0.09	15 46.43	1 30.61	0.545
Wed.	22	23 26 56.4	- 1.12	15 46.39	1 43.68	0.543
Thur.	23	23 26 17.1	2.16	15 46.35	1 56.68	0.540
Frid.	24	23 25 13.0	3.19	15 46.31	2 9.59	0.535
Sat.	25	23 23 44.2	- 4.22	15 46.28	2 22.37	0.530
SUN.	26	23 21 50.8	5.24	15 46.26	2 35.02	0.524
Mon.	27	23 19 32.7	6.26	15 46.24	2 47.49	0.516
Tues.	28	23 16 50.1	- 7.28	15 46.22	2 59.80	0.507
Wed.	29	23 13 43.0	8.30	15 46.21	3 11.87	0.498
Thur.	30	23 10 11.6	9.32	15 46.20	3 23.72	0.488
Frid.	31	N. 23 6 15.9	-10.32	15 46.19	3 35.32	0.478

## II.

JUNE, 1898

AT GREENWICH MEAN NOON

Day of the Week	Day of the Month	THE SUN'S		Equation of Time, to be		Diff. for 1 hour	Sidereal Time, or Right Ascension of Mean Sun
		Apparent Declination	Diff. for 1 hour	Added to			
				Subtracted from Mean Time			
		° ' "	"	m. s.	s.	b. m. s.	
Wed.	1	N. 22 6 1.6	+20.12	2 24.53	0.375	4 39 57.76	
Thur.	2	22 13 53.0	19.16	2 15.34	0.390	4 43 54.32	
Frid.	3	22 21 21.1	18.19	2 5.78	0.405	4 47 50.88	
Sat.	4	22 28 25.9	+17.21	1 55.86	0.420	4 51 47.44	
SUN.	5	22 35 7.1	16.22	1 45.58	0.435	4 55 43.99	
Mon.	6	22 41 24.7	15.23	1 34.99	0.448	4 59 40.55	
Tues.	7	22 47 18.4	+14.24	1 24.08	0.461	5 3 37.11	
Wed.	8	22 52 48.2	13.24	1 12.87	0.473	5 7 33.67	
Thur.	9	22 57 54.0	12.23	1 1.38	0.485	5 11 30.23	
Frid.	10	23 2 35.5	+11.22	0 49.61	0.495	5 15 26.78	
Sat.	11	23 6 52.7	10.21	0 37.62	0.504	5 19 23.34	
SUN.	12	23 10 45.6	9.19	0 25.40	0.513	5 23 19.90	
Mon.	13	23 14 13.9	+ 8.17	0 12.98	0.521	5 27 16.46	
Tues.	14	23 17 17.6	7.14	0 0.38	0.528	5 31 13.02	
Wed.	15	23 19 56.7	6.11	0 12.37	0.534	5 35 9.58	
Thur.	16	23 22 11.0	+ 5.08	0 25.26	0.538	5 39 6.13	
Frid.	17	23 24 0.6	4.05	0 38.24	0.542	5 43 2.69	
Sat.	18	23 25 25.4	3.02	0 51.28	0.545	5 46 59.25	
SUN.	19	23 26 25.4	+ 1.98	1 4.38	0.546	5 50 55.81	
Mon.	20	23 27 0.6	+ 0.94	1 17.49	0.546	5 54 52.37	
Tues.	21	23 27 10.9	- 0.09	1 30.60	0.545	5 58 48.92	
Wed.	22	23 26 56.4	- 1.12	1 43.66	0.543	6 2 45.48	
Thur.	23	23 26 17.2	2.15	1 56.66	0.540	6 6 42.04	
Frid.	24	23 25 13.1	3.18	2 9.57	0.535	6 10 38.60	
Sat.	25	23 23 44.4	- 4.21	2 22.35	0.530	6 14 35.16	
SUN.	26	23 21 51.0	5.24	2 35.00	0.524	6 18 31.72	
Mon.	27	23 19 33.0	6.26	2 47.47	0.516	6 22 28.28	
Tues.	28	23 16 50.5	- 7.28	2 59.77	0.507	6 26 24.83	
Wed.	29	23 13 43.5	8.30	3 11.84	0.498	6 30 21.39	
Thur.	30	23 10 12.1	9.31	3 23.69	0.488	6 34 17.95	
Frid.	31	N. 23 6 16.5	-10.32	3 35.29	0.478	6 38 14.51	

## FIXED STARS, 1898

## MEAN PLACES FOR THE BEGINNING OF 1898

Name of Star	Mag- nitude	Right Ascension		Annual Variation	Declination	Annual Variation
		h. m.	s.			
$\alpha$ Ursæ Min. ( <i>Polaris</i> )	2	1 21	43.70	+24.832	+88 45 49.1	+18.79
$\alpha$ Tauri ( <i>Aldebaran</i> )	1	4 30	4.02	3.438	+16 18 15.0	+ 7.48
$\alpha$ Aurigæ ( <i>Capella</i> )	1	5 9	9.19	4.426	+45 53 38.7	+ 3.98
$\beta$ Orionis ( <i>Rigel</i> )	1	5 9	38.13	2.882	- 8 19 10.5	+ 4.36
$\alpha$ Orionis ( <i>var.</i> )	1	5 49	38.96	3.247	+ 7 23 16.6	+ 0.91
$\alpha$ Canis Maj. ( <i>Sirius</i> )	1	6 40	39.21	2.644	-16 34 34.6	- 4.74
$\alpha$ Canis Min. ( <i>Procyon</i> )	1	7 33	57.77	3.143	+ 5 29 10.7	- 9.03
$\beta$ Geminorum ( <i>Pollux</i> )	1	7 39	4.53	3.678	+28 16 20.9	- 8.46
$\alpha$ Leonis ( <i>Regulus</i> )	1	10 2	56.43	3.200	+12 27 56.5	-17.49
$\alpha$ Virginis ( <i>Spica</i> )	1	13 19	49.10	3.155	-10 37 44.5	-18.89
$\alpha$ Bootis ( <i>Arcturus</i> )	1	14 11	0.53	2.735	+19 42 48.1	-18.86
$\alpha$ Scorpii ( <i>Antares</i> )	1	16 23	9.13	3.672	-26 12 20.5	- 8.26
$\alpha$ Lyræ ( <i>Vega</i> )	1	18 33	29.12	2.031	+38 41 18.8	+ 3.19
$\alpha$ Aquilæ ( <i>Altair</i> )	1	19 45	48.41	2.927	+ 8 35 55.7	+ 9.30

TABLE FOR FINDING THE LATITUDE BY AN OBSERVED ALTITUDE OF  
POLARIS

Reduce the observed altitude of Polaris to the true altitude.

Reduce the recorded time of observation to the local sidereal time.

If the sidereal time is  $\left\{ \begin{array}{l} \text{less than 1 h. 21.8 m., subtract it from 1 h.} \\ \text{21.8 m. ;} \\ \text{between 1 h. 21.8 m. and 13 h. 21.8 m., sub-} \\ \text{tract 1 h. 21.8 m. from it ;} \\ \text{greater than 13 h. 21.8 m., subtract it from} \\ \text{25 h. 21.8 m. ;} \end{array} \right.$

and the remainder is the hour angle of Polaris.

With this hour angle, take out the correction from Table (next page), and add it to or subtract it from the true altitude, according to its sign. The result is the approximate latitude of the place.

*Example.* — 1898, Oct. 1, at 10 h. 40 m. 30 s. P.M., mean solar time, in longitude  $29^\circ$  east of Greenwich, suppose the true altitude of Polaris to be  $43^\circ 20'$ ; required the latitude of the place.

	h. m. s.
Local astronomical mean time . . . . .	10 40 30
Reduction for 10 h. 40. m. 30 s. . . . .	+ 1 45
Greenwich sidereal time for mean noon, Oct. 1 . . . . .	12 40 58
Reduction for longitude (=1 h. 56 m. east, or minus),	<u>- 0 19</u>
Sum (having regard to signs) is equal to local sidereal time . . . . .	<u><u>23 22 54</u></u>

	h. m. s.
	25 21 48
Subtract sidereal time . . . . .	<u>23 22 54</u>
Remainder is equal to hour angle of Polaris . . . . .	1 58 54

True altitude . . . . .	+ 43 20
Correction from table (next page),	<u>- 1 4</u>
Approximate latitude . . . . .	+ 42 16

## CORRECTIONS TO ALTITUDE OF POLARIS. — 1898

Hour Angle		0 h.	1 h.	2 h.	3 h.	4 h.	5 h.
m.	0	-1 13.9 0.0	-1 11.3 0.4	-1 3.8 0.8	-0 51.9 1.2	-0 36.4 1.4	-0 18.4 1.5
	5	1 13.9 0.1	1 10.9 0.5	1 3.0 0.9	0 50.7 1.2	0 35.0 1.4	0 16.9 1.6
	10	1 13.8 0.1	1 10.4 0.5	1 2.1 0.9	0 49.5 1.2	0 33.6 1.5	0 15.3 1.6
	15	1 13.7 0.1	1 9.9 0.5	1 1.2 0.9	0 48.3 1.2	0 32.1 1.5	0 13.7 1.6
	20	-1 13.6 0.1	-1 9.4 0.6	-1 0.3 1.0	-0 47.1 1.3	-0 30.6 1.5	-0 12.1 1.6
	25	1 13.5 0.2	1 8.8 0.6	0 59.3 1.0	0 45.8 1.3	0 29.1 1.5	0 10.5 1.6
	30	1 13.3 0.2	1 8.2 0.7	0 58.3 1.0	0 44.5 1.3	0 27.6 1.5	0 8.9 1.6
	35	1 13.1 0.3	1 7.5 0.7	0 57.3 1.0	0 43.2 1.3	0 26.1 1.5	0 7.3 1.6
	40	-1 12.8 0.3	-1 6.8 0.7	-0 56.3 1.1	-0 41.9 1.4	-0 24.6 1.5	-0 5.7 1.6
	45	1 12.5 0.4	1 6.1 0.7	0 55.2 1.1	0 40.5 1.3	0 23.1 1.5	0 4.1 1.6
	50	1 12.1 0.4	1 5.4 0.8	0 54.1 1.1	0 39.2 1.4	0 21.6 1.6	0 2.5 1.6
	55	1 11.7 0.4	1 4.6 0.8	0 53.0 1.1	0 37.8 1.4	0 20.0 1.6	-0 0.9 1.7
	60	-1 11.3	-1 3.8 0.8	-0 51.9 1.1	-0 36.4 1.4	-0 18.4 1.6	+0 0.8 1.7

Hour Angle		6 h.	7 h.	8 h.	9 h.	10 h.	11 h.
m.	0	+0 0.8 1.6	+0 19.8 1.6	+0 37.6 1.4	+0 52.6 1.1	+1 4.2 0.8	+1 11.4 0.4
	5	0 2.4 1.6	0 21.4 1.5	0 39.0 1.3	0 53.7 1.1	1 5.0 0.7	1 11.8 0.4
	10	0 4.0 1.6	0 22.9 1.6	0 40.3 1.3	0 54.8 1.1	1 5.7 0.7	1 12.2 0.3
	15	0 5.6 1.6	0 24.5 1.5	0 41.6 1.3	0 55.9 1.0	1 6.4 0.7	1 12.5 0.3
	20	+0 7.2 1.6	+0 26.0 1.5	+0 42.9 1.3	+0 56.9 1.0	+1 7.1 0.7	+1 12.8 0.3
	25	0 8.8 1.6	0 27.5 1.5	0 44.2 1.3	0 57.9 1.0	1 7.8 0.6	1 13.1 0.2
	30	0 10.4 1.6	0 29.0 1.5	0 45.5 1.3	0 58.9 1.0	1 8.4 0.5	1 13.3 0.2
	35	0 12.0 1.6	0 30.5 1.4	0 46.8 1.2	0 59.9 0.9	1 8.9 0.5	1 13.5 0.1
	40	+0 13.6 1.6	+0 31.9 1.4	+0 48.0 1.2	+1 0.8 0.9	+1 9.4 0.5	+1 13.6 0.1
	45	0 15.2 1.6	0 33.3 1.5	0 49.2 1.2	1 1.7 0.9	1 9.9 0.5	1 13.7 0.1
	50	0 16.8 1.5	0 34.8 1.4	0 50.4 1.1	1 2.6 0.8	1 10.4 0.5	1 13.8 0.1
	55	0 18.3 1.5	0 36.2 1.4	0 51.5 1.1	1 3.4 0.8	1 10.9 0.5	1 13.9 0.0
	60	+0 19.8	+0 37.6 1.4	+0 52.6 1.1	+1 4.2 0.8	+1 11.4 0.5	+1 13.9 0.0

**CORRECTIONS**

**TO**

**MIDDLE LATITUDE**

## DIFFERENCE OF LATITUDE

Mid. Lat.	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°	19°	20°	Mid. Lat.
15	-79	-76	-79	-82	-79	-75	-71	-68	-64	-58	-53	-49	-44	-39	-32	-26	-20	-12	4	15
16	-74	-77	-74	-72	-70	-69	-66	-61	-57	-54	-50	-44	-39	-35	-29	-23	-16	-8	2	16
17	-73	-70	-68	-67	-63	-61	-59	-57	-54	-50	-44	-41	-36	-31	-25	-19	-13	-6	0	17
18	-67	-67	-63	-60	-59	-55	-54	-51	-48	-46	-42	-37	-32	-27	-22	-16	-10	-4	2	18
19	-58	-58	-58	-58	-55	-53	-50	-49	-45	-41	-37	-34	-30	-24	-19	-14	-8	-1	4	19
20	-53	-53	-53	-53	-51	-51	-47	-44	-41	-38	-34	-29	-26	-21	-17	-11	-4	0	6	20
21	-53	-53	-49	-50	-48	-46	-43	-41	-38	-34	-31	-27	-23	-18	-14	-10	-4	2	8	21
22	-49	-51	-49	-47	-44	-42	-40	-37	-35	-32	-28	-24	-21	-17	-12	-6	-1	3	9	22
23	-48	-48	-45	-43	-42	-39	-37	-34	-32	-29	-26	-23	-18	-14	-9	-5	0	6	11	23
24	-45	-41	-42	-40	-39	-37	-35	-32	-30	-27	-23	-19	-16	-12	-8	-3	2	7	13	24
25	-40	-38	-40	-37	-36	-34	-33	-30	-27	-24	-21	-18	-14	-10	-6	-2	3	9	14	25
26	-38	-35	-35	-34	-34	-32	-30	-27	-25	-22	-19	-16	-12	-8	-4	-1	4	10	16	26
27	-35	-34	-35	-33	-31	-29	-28	-25	-23	-21	-17	-14	-9	-6	-2	2	7	12	17	27
28	-34	-34	-32	-30	-29	-27	-26	-23	-22	-18	-15	-12	-9	-5	0	4	9	13	19	28
29	-32	-31	-30	-29	-28	-26	-24	-21	-19	-16	-14	-10	-7	-3	1	5	10	15	20	29
30	-29	-29	-29	-28	-26	-24	-22	-20	-18	-14	-11	-8	-5	-1	3	7	12	16	21	30
31	-29	-27	-27	-26	-25	-22	-20	-18	-15	-13	-10	-7	-3	1	4	9	13	18	23	31
32	-28	-28	-26	-23	-22	-21	-19	-17	-13	-12	-9	-5	-2	2	6	10	14	19	24	32
33	-26	-23	-24	-23	-21	-19	-17	-15	-13	-10	-7	-4	0	3	7	12	16	21	25	33
34	-23	-22	-21	-21	-19	-18	-16	-13	-11	-8	-6	-2	1	5	8	13	17	22	27	34
35	-20	-21	-20	-19	-18	-16	-14	-12	-10	-7	-4	-1	2	6	10	14	19	23	28	35
36	-20	-21	-19	-17	-16	-14	-13	-11	-9	-6	-3	0	4	7	11	15	20	25	31	36
37	-20	-18	-17	-16	-15	-13	-12	-9	-7	-6	-2	2	5	9	13	17	21	26	32	37
38	-17	-16	-17	-15	-14	-12	-10	-8	-6	-3	0	3	6	10	14	18	22	27	33	38
39	-17	-15	-16	-14	-13	-11	-9	-7	-4	-2	1	4	8	11	14	19	24	29	33	39
40	-17	-17	-14	-13	-12	-10	-8	-6	-3	-1	2	6	9	13	17	21	25	30	35	40



Mid. Lat.	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°	19°	20°	Mid. Lat.
41	-15	-15	-14	-12	-10	-9	-7	-4	-3	0	+3	+6	+10	+14	+18	+22	+26	+31	+36	41
42	-14	-13	-11	-10	-9	-8	-6	-3	-1	+2	+4	+8	+12	+15	+19	+23	+28	+33	+38	42
43	-11	-12	-11	-10	-9	-8	-6	-4	0	+3	+5	+9	+14	+16	+20	+24	+29	+34	+39	43
44	-11	-10	-10	-9	-8	-6	-4	-2	0	+2	+7	+11	+15	+17	+21	+26	+30	+35	+41	44
45	-12	-10	-9	-7	-6	-5	-4	-2	+3	+6	+9	+12	+15	+19	+23	+28	+33	+38	+42	45
46	-11	-9	-9	-7	-6	-5	-4	-2	+1	+4	+7	+10	+13	+17	+21	+25	+30	+34	+39	46
47	-8	-9	-8	-6	-5	-4	-3	-1	+1	+4	+6	+9	+12	+16	+20	+24	+29	+33	+38	47
48	-9	-8	-7	-6	-4	-2	-1	+1	+2	+5	+8	+11	+14	+18	+22	+26	+31	+36	+41	48
49	-8	-7	-6	-5	-3	-2	0	+3	+5	+8	+11	+15	+17	+23	+27	+32	+37	+42	+48	49
50	-6	-6	-6	-4	-3	-1	+1	+3	+6	+9	+12	+16	+20	+24	+29	+33	+38	+44	+51	50
51	-7	-6	-5	-4	-2	0	+2	+4	+7	+10	+14	+17	+21	+25	+30	+35	+40	+45	+51	51
52	-7	-6	-4	-3	-1	0	+3	+5	+8	+11	+15	+18	+22	+26	+31	+36	+41	+47	+53	52
53	-5	-5	-5	-3	-1	+1	+4	+6	+9	+12	+16	+20	+23	+28	+32	+37	+43	+48	+55	53
54	-6	-4	-3	-2	0	+2	+4	+7	+9	+13	+16	+20	+24	+29	+34	+39	+44	+50	+56	54
55	-5	-4	-2	-2	0	+2	+4	+7	+10	+14	+17	+21	+25	+30	+35	+40	+46	+52	+58	55
56	-3	-4	-3	-1	+1	+3	+5	+8	+11	+15	+18	+22	+27	+31	+37	+42	+48	+54	+60	56
57	-4	-3	-2	0	+1	+4	+6	+9	+12	+15	+19	+23	+28	+33	+38	+44	+49	+55	+62	57
58	-4	-2	-1	0	+2	+4	+7	+10	+13	+16	+20	+25	+29	+34	+39	+45	+51	+58	+65	58
59	-3	-2	-1	+1	+2	+5	+8	+10	+14	+17	+21	+26	+30	+36	+41	+47	+53	+60	+67	59
60	-2	-2	0	+1	+3	+5	+8	+11	+15	+18	+22	+27	+32	+37	+43	+49	+55	+62	+69	60
61	-2	-1	0	+2	+4	+6	+9	+12	+15	+20	+24	+28	+33	+39	+44	+52	+57	+64	+72	61
62	-1	-1	0	+2	+4	+7	+9	+13	+16	+20	+25	+29	+35	+40	+46	+53	+60	+67	+75	62
63	-1	-1	+1	+3	+4	+7	+10	+14	+17	+21	+26	+31	+36	+42	+48	+55	+62	+70	+78	63
64	-1	0	+1	+3	+5	+8	+11	+14	+18	+22	+27	+32	+38	+44	+50	+57	+65	+73	+81	64
65	-1	0	+1	+3	+6	+8	+12	+15	+19	+24	+29	+34	+40	+46	+53	+60	+68	+76	+85	65
66	-1	+1	+2	+4	+6	+9	+12	+16	+20	+25	+30	+35	+42	+48	+55	+63	+71	+80	+89	66
67	-1	0	+2	+4	+7	+10	+13	+17	+21	+26	+31	+37	+44	+50	+58	+66	+74	+83	+93	67
68	0	+1	+2	+4	+7	+10	+14	+18	+22	+28	+33	+39	+46	+53	+61	+69	+78	+88	+98	68
69	0	+1	+3	+5	+8	+11	+15	+19	+24	+29	+35	+41	+48	+56	+64	+73	+82	+92	+103	69
70	0	+1	+3	+5	+8	+12	+16	+20	+25	+30	+37	+43	+51	+59	+67	+77	+87	+97	+109	70

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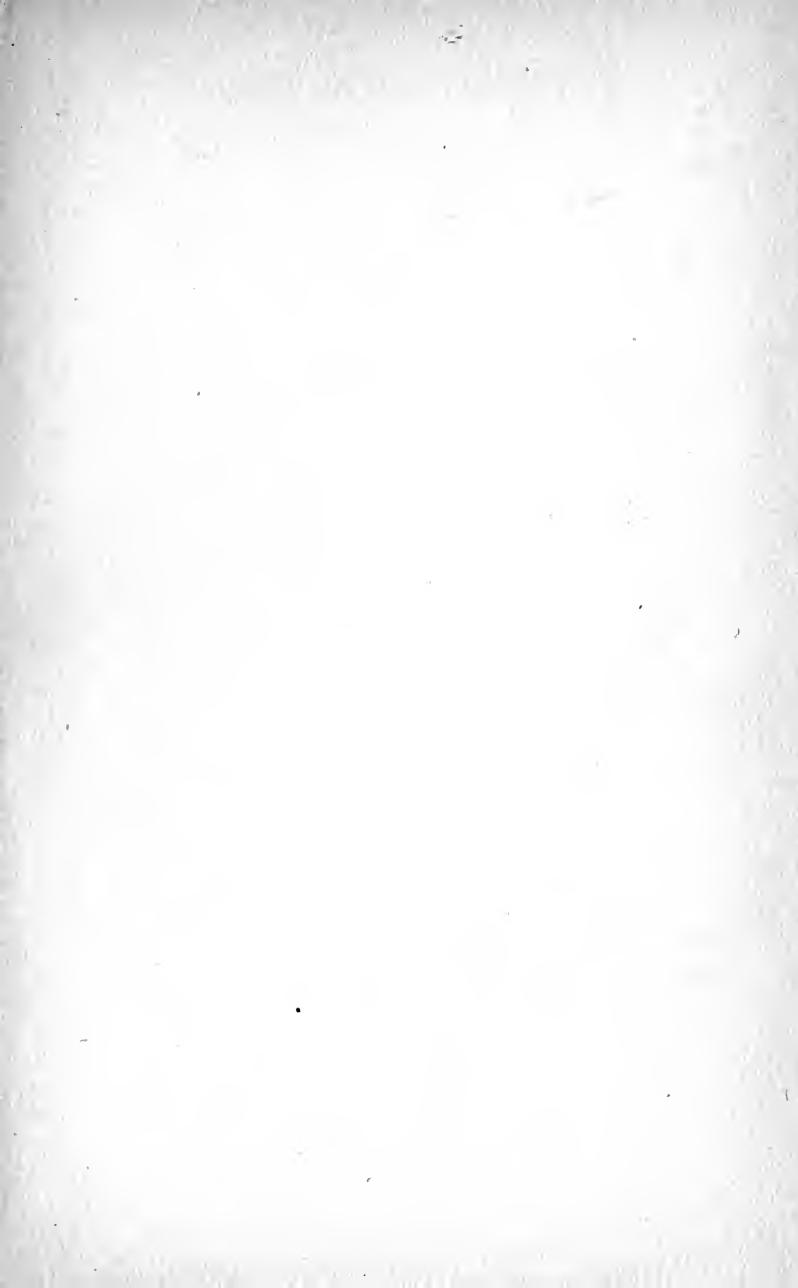
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