COMPENDIUM

FOR APPLIED

MATHEMATICAL NAVIGATION

Sixth edition:	15 December 2012
Fifth edition:	27 August 2010
Forth edition:	19 December 2009
Third edition:	14 October 2009
Second edition:	19 March 2009
First edition:	28 December 2008
First issue:	28 February 2007

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PART 1

(Fundamentals)

Chapter 1

(Terms and conventions)

1110 Navigation methods

The navigator shall always use all methods and techniques adequate to the vessel its equipment and the prevailing conditions at sea. However, as each method has its advantages and disadvantages and as no method is equal effective on all situations, one of the navigator's most important decisions is to select the best methods to be used in the prevailing situation and to synthesize the selected methodologies into a single integrated system.

Navigation methods have changed throughout the centuries. However, the following methods are widely accepted today:

- **Dead reckoning (DR)** involves determination of the position by advancing a known position for courses and distances derived from the vessel's speed. A position determined by course and speed only is called the dead reckoning position. Corrections of the dead reckoning position for steering errors, current influences and leeway lead to the **estimated position (EP).**

- **Terrestrial navigation** involves navigation in geographically restricted areas by fixing the position of the vessel as precisely as possible relative to nearby geographic and hydrographical features.

- **Celestial navigation** involves reduction of celestial observations obtained by a sextant to lines of position, using almanacs and specific tables or almanacs and handheld calculators, to solve the appropriate spherical trigonometry equations.

- **Radar navigation** involves the use of radar equipment to determine the distance of the vessel to an object, whose position is known and the objects bearing relative to the vessels longitudinal axis.

- **Satellite navigation** involves the use of satellite signals by sophisticated electronics to determine the vessel's geographic position, its true course and the vessel's speed over ground.

Today's sophisticated electronic systems enable us to establish and operate integrated bridge concepts involving determination and display of the vessel's actual speed and position, as well as the generation of appropriate commands to maintain the vessel on the desired course whereas the navigator acts as a system manager, selecting information sources, initializing system presets and monitoring the vessel's responses. In fact modern navigation is almost completely an automated electronic process.

However taking into account that electronic equipment and instrumentation, even if operated in a protected environment, are subject to random failures, the professional navigator shall always be able to safely navigate the vessel by means of terrestrial and celestial navigation methods.

1111 Navigational conventions

In order to be able to understand the fundamentals of navigation it is a matter of paramount importance to have a clear picture of the following important conventions.

- **Nautical charts** in paper or digital form are graphical representations of the Earth for marine navigation purposes. The standard projection of nautical charts is the Mercator projection.

- **Sailing directions or pilots** are handbooks containing useful information for the navigator, which cannot be implemented in the nautical charts.

- **Variation** is the angular difference between the great circle connecting the geographic poles, called the true meridian, and the direction of the lines of magnetic flux, called the magnetic meridian. This variation has different values at different Earth locations. Information about the values of the variation for a specific Earth location can be extracted from the nautical charts applicable for this location.

- **Deviation** is the magnetic compass card deflection right or left of the magnetic meridian, caused by the magnetic properties of the environment in which the compass is installed and the misalignment between the NS-axis of the compass card and the vessel's longitudinal axis.

- **Magnetic compass** is a device sensitive to Earth magnetism and is used still today in form of a dry card marine compass as heading reference. To convert the magnetic compass reading to true heading corrections for deviation and variation must be applied.

- **Flux gate compass** is still a magnetic compass, but it has no moving parts and can compensate himself for deviation and variation thus, providing true heading as its output.

- **Gyrocompasses** are electromechanical gyroscopic devices providing true heading with high accuracy. They have been further improved by the introduction of inertial navigation systems. However, as all gyroscopic devices are depending upon the continuous availability of electrical power and are involving a lot of mechanical moving parts, they are considered to be sensitive to failures and can therefore not eliminate the need to use a magnetic compass as a back-up element.

- **Ring laser gyrocompasses** are high accuracy devices with no moving parts. These devices do not operate on the gyroscopic principle, but instead relay on the principles of the wave theory.

- A **log is** the mariner's speedometer and its reading is the vessel's speed through water in knots.

- **Prime Meridian** is the meridian of Greenwich which is used to measure longitude, both east and west through 180°.

1120 The Earth

The Earth is an irregular oblate spheroid i.e. a sphere flattened at the poles. However, for most navigational purposes no significant errors will be introduced assuming a spherical Earth. The Earth's axis of rotation is the line connecting the **geographic north and south pole**.

A **great circle** is the line of intersection of a sphere and a plane through its centre and it is the largest circle that can be drawn on a sphere. The shortest line between two points on the surface of the sphere is part of the great circle.

The term **meridian** is applied to the **upper branch** of the half circle from pole to pole which passes through a given point, whilst the opposite half is called the **lower branch**.

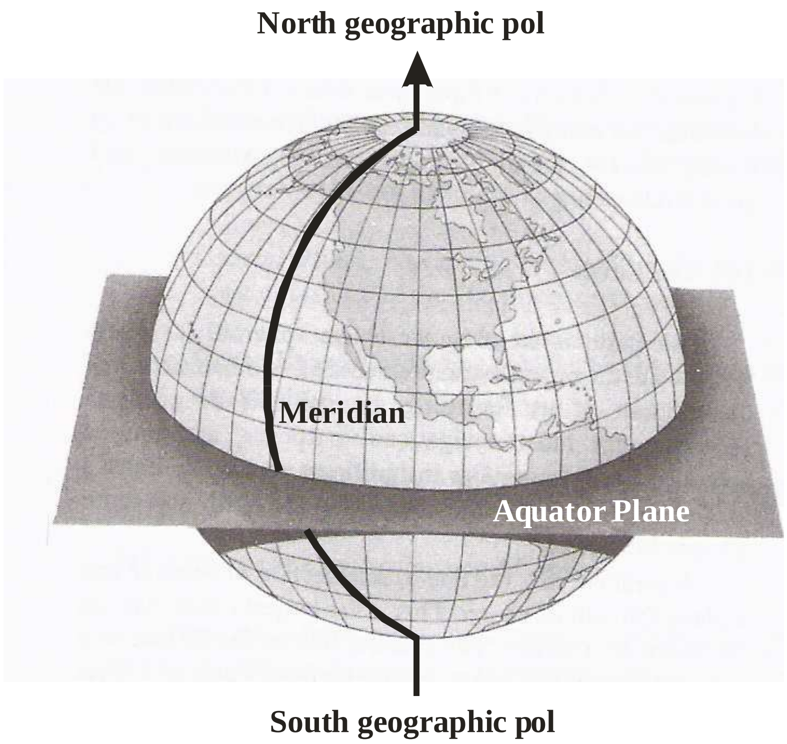


Figure 1120 Great circle of equator and meridian

The parallel of latitude called the **parallel** is a circle on the surface of the Earth parallel to the plane of the equator. Said circle represents the geometric location of all points of equal latitude (ref. Figure 1120).
- The equator parallel is a great circle of 0° latitude.
- The poles are single points of 90° latitude.
- All other parallels are circles smaller than the equator parallel.

1121 Earth coordinates

Any position on the Earth surface can be defined by the Earth coordinates named **latitude** and **longitude.**

- **Latitude (φ)** is the angular distance from the equator, measured northward or southward along a meridian from 0° at the equator, to 90° at the poles, and is designated north **(N)** or south **(S)** to indicate the direction of measurement.

- The **difference of latitude (Δφ)** between two places is the angular length of any meridian between their parallels. Its value is the arithmetic difference of the latitudes if the places are on the same side of the equator, but the sum of the latitudes, when situated on opposite sides of the equator and can be designated **(N)** or **(S)** as appropriate.

- The **mid latitude (φm)** between two places on the same side of the equator is the arithmetic mean value of the latitudes of the places and is labelled **(N)** or **(S)** to indicate whether it is north or south of the equator. If the places are on opposite sides of the equator, the mid latitude is half the difference between the two latitudes and takes the name of the place furthest from the equator.

- The **longitude (λ)** is the angular distance between the prime meridian and the meridian of a point on the Earth measured eastward or westward of the prime meridian through 180°. It is designated east **(E)** or west **(W)** to indicate the direction of measurement.

- The **difference of longitude (Δλ)** between two places is the angular length of the shortest parallel between their meridians. If both places are on the same side (east or west) of the prime meridian, the difference of longitude is the arithmetic difference between both longitudes. If on opposite side, the difference of longitude is the sum of the values unless this sum exceeds 180°, then it is 360° minus the sum. The difference of longitude may be designated **(E)** or **(W)** as appropriate.

- The distance between two meridians at any parallel expressed in nautical miles **(Sm)** is called **departure (p)** and represents the distance made good eastward or westward**.** Its numerical value between any two meridians decreases with increasing latitude, whilst the difference of longitude remains constant at any latitude. On the equator parallel the values of the difference of longitude and the departure, if both are expressed in arc minutes, are identical. With increasing latitude, decrease of the departure can approximately be computed by:

$$p_{\varphi i} = \Delta\lambda_{\varphi i} * \cos\varphi_i \,.$$

The departure may be designated **(E)** or **(W)** as appropriate.

1122 Distance and speed on the Earth

Distance, as used by the navigator, is the length of the Rhumb line connecting two places. This is a line making the same angle with all meridians. Meridians and parallels which also maintain constant true directions may be considered special cases of the Rhumb line. Any other Rhumb line spirals toward the pole, forming a loxodromic curve or loxodrome (Ref. Figure 1122). Distance along the great circle connecting two points is customarily designated great-circle distance. For most purposes, considering the nautical mile the length of one minute of latitude introduces no significant error

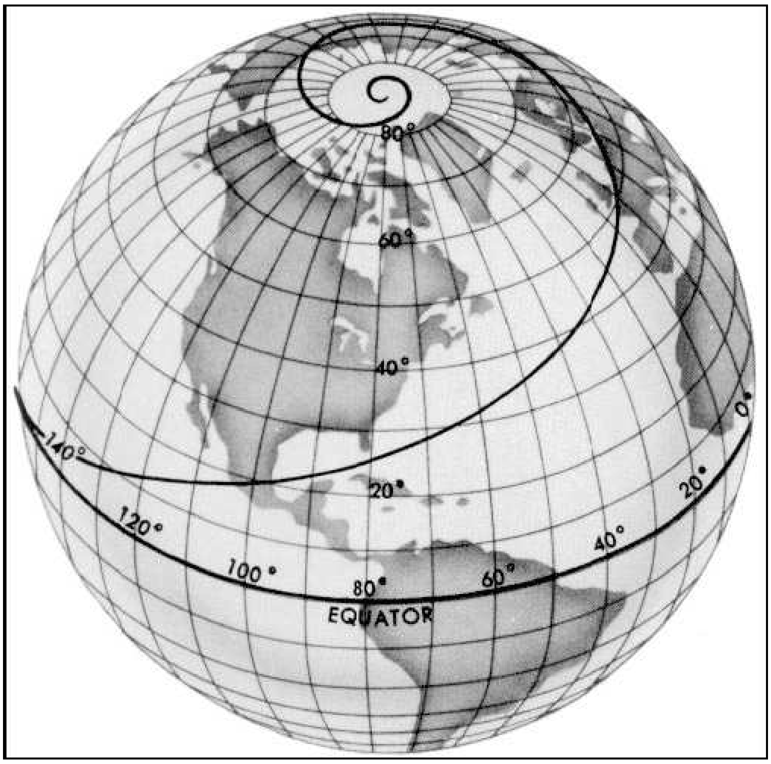


Figure 1122 A loxodrome

Speed is rate of motion, or distance per unit of time. A knot **(kn.)**, the unit of speed commonly used in navigation, is a rate of one nautical mile per hour. Speed over the ground **(SOG)** is the actual speed of the vessel over the surface of the Earth at any given time. To calculate speed made good **(SMG)** between two positions, divide the distance between the two positions by the time elapsed between the two positions.

1123 Direction on the Earth

Direction is the position of one point relative to another. Navigators express direction as the angular difference in degrees from a reference direction, usually north or the ship's head. Course **(C, Cn)** is the horizontal direction in which a vessel is intended to be steered, expressed as angular distance from north clockwise through 360°. Strictly used, the term applies to direction through the water, not the direction intended to be made good over the ground. The course is often designated as true, magnetic, compass, or grid according to the reference direction.

Track made good **(TMG)** is the single resultant direction from the point of departure to point of arrival at any given time. Course of advance **(COA)** is the direction intended to be made good over ground, and course over ground **(COG)** is the direction between a vessel's last fix and an EP. A course line is a line drawn on a chart extending in the direction of a course. It is sometimes convenient to express a course as an angle from either north or south, through 90° or 180°. In this case it is the designated course angle (C) and should be properly labelled to indicate the origin **(prefix)** and direction of measurement **(suffix)**. Thus,

- C N35°E = Cn 035° (000° + 35°),
- C N155°W = Cn 205° (360° - 155°),
- C S47°E = Cn 133° (180° - 47°).
- But Cn 260° may be either C N100°W or C S80°W, depending upon the conditions of the problem.

Track **(TR)** is the intended horizontal direction of travel with respect to the Earth. The terms intended track and track line are used to indicate the path of intended travel (Ref. Figure 1123). The track consists of one or a series of course lines, from the point of departure to the destination, along which one intends to proceed. A great circle which a vessel intends to follow is called a great-circle track, though it consists of a series of straight lines approximating a great circle. Heading **(Hdg., SH)** is the direction in which a vessel is pointed at any given moment, expressed as angular distance from 000° clockwise through 360°. It is easy to confuse heading and course. Heading constantly changes as a vessel yaws back and forth across the course due to sea, wind, and steering error.

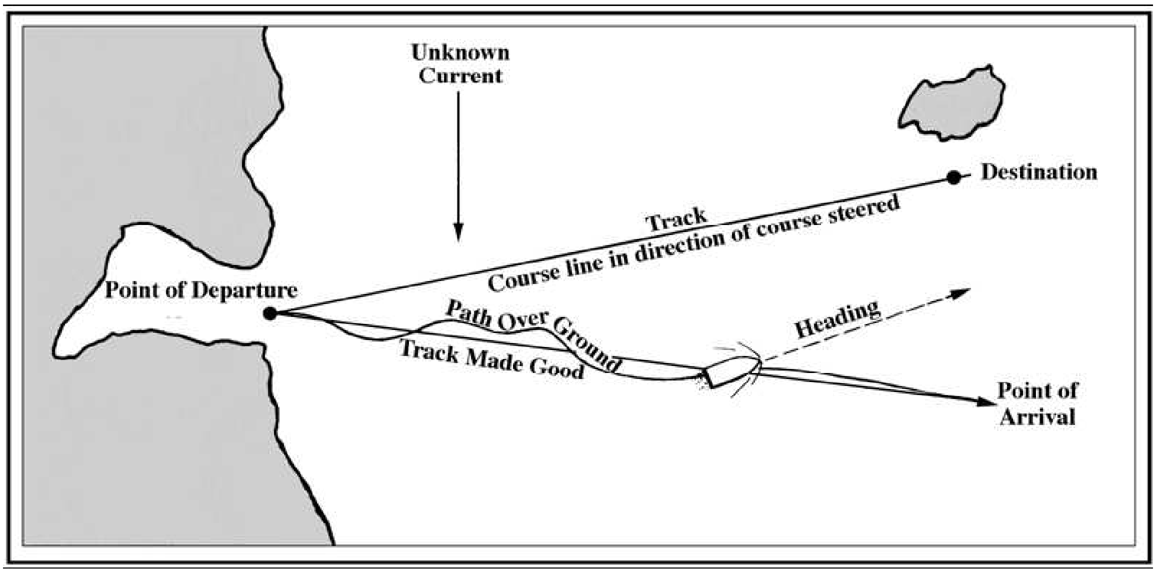


Figure 1123 Course line, track, track made good, and heading.

Bearing **(B, Brg.)** is the direction of one terrestrial point from another, expressed as angular distance from 000° (North) clockwise through 360°. When measured through 90° or 180° from either north or south, it is called bearing angle (B). Bearing and azimuth are sometimes used interchangeably, but the latter more accurately refers to the horizontal direction of a point on the celestial sphere from a point on the Earth. A relative bearing is measured relative to the ship's heading from 000° (dead ahead) clockwise through 360°. However, it is sometimes conveniently measured right or left from 000° at the ship's head through 180°.

PART 1

(Fundamentals)

Chapter 2

(Charts / Chart projections)

1210 Nautical charts

A nautical chart is primarily intended for navigation. It generally shows depths of water by soundings and same times also by depth curves, aids to navigation, dangers, and the outline of adjacent land and such land features useful to the navigator.

Chart making presents the problem of representing the surface of a spheroid upon a plane surface. The surface of a sphere or spheroid is said to be **undevelopable** because no part of it can be flattened without distortion. A chart projection is a method of representing all or part of the surface of a sphere or spheroid upon a plane surface. The process is one of transferring points of the surface of the sphere or the spheroid onto a plane, or onto a developable surface such as cylinder or cone.

Each projection has distinctive features which make it preferable for certain uses, no one projection being best for all conditions: Some of the desirable properties are:

- *True shape of physical features.*
- *Correct angular relationship (**Conformal or orthomorphic projection**).*
- *Equal area (representation of areas in their correct relative proportions).*
- *Constant scale values for measuring distances.*
- *Great circles represented as straight lines.*
- *Rhumb lines represented as straight lines.*

It is possible to preserve any one and some times more than one property in any one projection, but it is impossible to preserve all of them. For instance, a projection cannot be conformal and equal area, nor can both great circles and Rhumb lines represented as strait lines.

1211 Selecting a projection

For marine charts a conformal projection upon a plane is used the so called **Mercator projection**. For explanation of the development of the projection the tangent cylinder can be used. The Mercator projection is not perspective and the parallels cannot be located by geometrical projection, the spacing being derived mathematically.

The distinguishing feature of the Mercator projection among other projections is that both the meridians and the parallels are expanded at the same ratio with increased latitude. The expansion is equal to the secant of the latitude, with a small correction for the ellipticity of the Earth. Since the secant of 90° is infinity, the projection can not include the poles. Expansion is the same on all directions and angles are correctly shown, the projection being conformal.

Rhumb lines appear as strait lines, the directions of which can be measured directly on the chart. Distances can also be measured directly, to practical accuracy, but not by a single distance scale over the entire chart, unless the spread of latitude is small. The latitude scale is customary used for measuring distances, the expansion of the scale being the same as that of distances at the same latitude. Great circles, except meridians and the equator, appear as curved lines concave to the equator.

Small areas appear in their correct shape but of increased size unless they are near the equator. Plotting of positions by latitude and longitude is done by means of rectangular coordinates, as on any cylinder projection.

1212 Plotting sheets

Plotting sheets are primarily designed for plotting the dead reckoning and lines of position obtained from celestial observations or radio aids to navigation. They have the latitude and longitude gratitude, but little or no additional information.

Plotting sheets are less expensive to produce than charts and are equally suitable or superior for some purposes. They are used primarily when land, visual aids to navigation and depth of water are not important.

A Mercator plotting sheet for relative small sailing area can be produced by the navigator with a good approximation, using the cosines of latitude method, which approximates the expansion. An example for a plotting sheet for mid latitude of 40° N is showed in Figure 1212 below.

The distance between meridians can be graphically determined as shown in Figure 1212, or calculated by multiplying the distance representing 1° of latitude on the vertical axis of the sheet by the cosine of the mid latitude. In the example below the distance between the meridians is represented by the distance between the parallels reduced by the factor 0,766 which is nothing else than the cosine of the mid latitude of 40°.

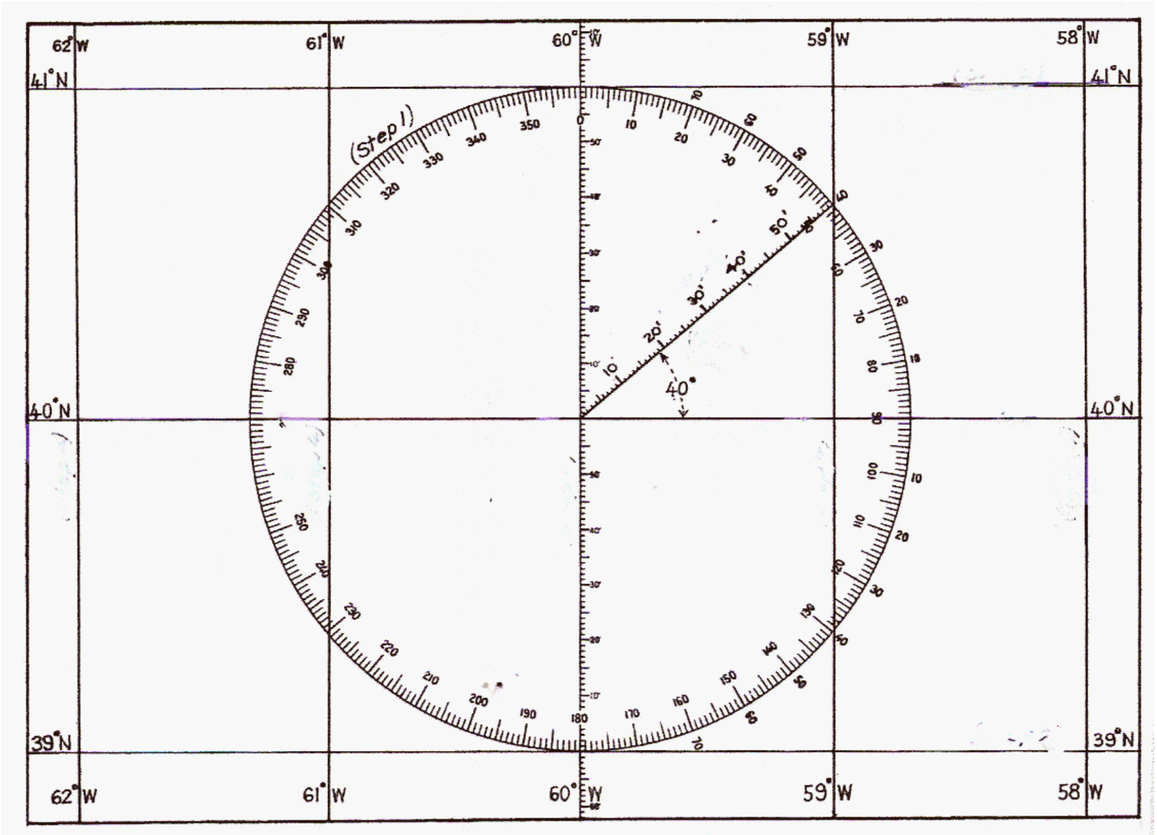


Figure 1212 Plotting sheet

,PART 2

(Terrestrial navigation)

Chapter 1

(Instruments for piloting and dead reckoning)

2110 Magnetic compass

Directional information is of such importance that selection and installation of a suitable compass should be made carefully, seeking such guidance as may be needed.

After the compass has been selected and installed, proper adjustment and compensation are important, and future care of the instrument should not be neglected. It should be checked at regular intervals, and any indication of malfunctioning or deterioration, however slight, should not be overlooked. Discoloration of the liquid or the presence of bubbles, indicate a condition that should be immediately investigated and corrected.

2111 Magnetic compass error

The following expressions of a direction should be clearly kept in mind:

- True and magnetic directions differ by the **variation**.
- Magnetic and compass directions differ by the **deviation**.
- True and compass directions differ by the **compass error**.

If variation or deviation is easterly, the compass card is rotated in a clockwise direction and brings therefore smaller numbers opposite the lubber's line. Conversely, if the either error is westerly, the rotation is counter clockwise and larger numbers are brought opposite the lubber's line.

Example: *A vessel is on course 215° true in an area where the variation is 7° W. The deviation on this heading is 1,5° W. A lighthouse bears 306,5° by magnetic compass. Required: 1) Magnetic heading. 2) Compass heading. 3) Compass error. 4) Magnetic bearing of the lighthouse. 5) True bearing of the lighthouse. 6) Relative (Side) bearing of the lighthouse.*

Answer:

1) ***215°+7° = 222°***
2) ***215°+7°+1,5° = 223,5°***
3) ***7°+1,5° = 8,5°***
4) ***306,5°-1,5° = 305°***
5) ***306,5°-1,5°-7° = 298°***
6) ***298°-215° = 83°***

2112 Compass deviation analysis

For the purpose of the analysis, easterly deviation is considered positive, and westerly deviation negative.

The values of the various coefficients are determined as follows:

- A) Mean deviation on all headings.
- B) Mean deviation on headings 090° and 270°, with sign at 270° reversed.
- C) Mean deviation on headings 000° and 180°, with sign at 180° reversed.
- D) Mean deviation on intercardinal headings, with signs at 135° and 315° reversed.
- E) Mean deviation on cardinal headings, with signs at 090° and 270° reversed.
- F) Mean deviation on headings 030°, 090°, 150°, 210°, 270° and 330°, with signs at 090°, 210°, and 330° reversed.
- G) Mean deviation on headings 000°, 060°, 120°, 180°, 240° and 300°, with signs at 060°, 180°, and 300° reversed.

For a vessel on an even keel, the total deviation (d) on any compass heading (CH) is the algebraic sum of the deviation due to each of the first seven coefficients:

$$d = d_A + d_B + d_C + d_D + d_E + d_F + d_G$$

$$d = A + B \bullet \sin CH + C \bullet \cos CH + D \bullet \sin 2CH + E \bullet \cos 2CH + F \bullet \sin 3CH + G \bullet \cos 3CH$$

Example: *A magnetic compass which has not been adjusted has the following deviations. Required: 1) The approximate value of each coefficient. 2)The deviation of each coefficient acting alone and the total deviation of the unadjusted compass.*

Compass Heading	*Deviation*	*Compass heading*	*Deviation*
000°	*1,5°W*	*180°*	*8°E*
030°	*35.5°E*	*210°*	*0,5°E*
045°	*34°E*	*225°*	*1,5°W*
060°	*33°E*	*240°*	*4,5°W*
090°	*31°E*	*270°*	*29°W*
120°	*23°E*	*300°*	*31°W*
135°	*13,5°E*	*315°*	*36°W*
150°	*11,5°E*	*330°*	*23°W*

Answer: ***1) The approximate value of each coefficient is:***

$$A = \frac{-1,5 + 35,5 + 34 + 33 + 31 + 23 + 13,5 + 11,5 + 8 + 0,5 - 1,5 - 4,5 - 29 - 31 - 36 - 23}{16} = +3,97°$$

$$B = \frac{31 + 29}{2} = +30°$$

$$C = \frac{-1,5 - 8}{2} = -4,75°$$

$$D = \frac{34 - 13,5 - 1,5 + 36}{4} = +13,75°$$

$$E = \frac{-1{,}5 - 31 + 8 + 29}{4} = +1{,}13°$$

$$F = \frac{35{,}5 - 31 + 11{,}5 - 0{,}5 - 29 + 23}{6} = +1{,}58°$$

$$G = \frac{-1{,}5 - 33 + 23 - 8 - 4{,}5 + 31}{6} = +1{,}17°$$

2) ***The deviation on any compass heading (CH) of each coefficient acting alone and the total deviation are calculated in the table below:***

CH	**dA** A=3,97	**dB** 30*sinCH	**dC** -4,75*cosCH	**dD** 13,75*sin2CH	**dE** 1,13*cos2CH	**dF** 1,58*sin3CH	**dG** 1,17*cos3CH	**d** Total
0	4,0	0,0	-4,8	0,0	1,1	0,0	1,2	1,5
15	4,0	7,8	-4,6	6,9	1,0	1,1	0,8	16,9
30	4,0	15,0	-4,1	11,9	0,6	1,6	0,0	28,9
45	4,0	21,2	-3,4	13,8	0,0	1,1	-0,8	35,9
60	4,0	26,0	-2,4	11,9	-0,6	0,0	-1,2	37,7
75	4,0	29,0	-1,2	6,9	-1,0	-1,1	-0,8	35,7
90	4,0	30,0	0,0	0,0	-1,1	-1,6	0,0	31,3
105	4,0	29,0	1,2	-6,9	-1,0	-1,1	0,8	26,0
120	4,0	26,0	2,4	-11,9	-0,6	0,0	1,2	21,0
135	4,0	21,2	3,4	-13,8	0,0	1,1	0,8	16,7
150	4,0	15,0	4,1	-11,9	0,6	1,6	0,0	13,3
165	4,0	7,8	4,6	-6,9	1,0	1,1	-0,8	10,7
180	4,0	0,0	4,8	0,0	1,1	0,0	-1,2	8,7
195	4,0	-7,8	4,6	6,9	1,0	-1,1	-0,8	6,7
210	4,0	-15,0	4,1	11,9	0,6	-1,6	0,0	4,0
225	4,0	-21,2	3,4	13,8	0,0	-1,1	0,8	-0,4
240	4,0	-26,0	2,4	11,9	-0,6	0,0	1,2	-7,1
255	4,0	-29,0	1,2	6,9	-1,0	1,1	0,8	-15,9
270	4,0	-30,0	0,0	0,0	-1,1	1,6	0,0	-25,6
285	4,0	-29,0	-1,2	-6,9	-1,0	1,1	-0,8	-33,8
300	4,0	-26,0	-2,4	-11,9	-0,6	0,0	-1,2	-38,0
315	4,0	-21,2	-3,4	-13,8	0,0	-1,1	-0,8	-36,3
330	4,0	-15,0	-4,1	-11,9	0,6	-1,6	0,0	-28,1
345	4,0	-7,8	-4,6	-6,9	1,0	-1,1	0,8	-14,6

Since the various coefficients are only approximated by the method given above, the curve of the total deviation found in this way should not be expected to coincide exactly with the curve drawn from values found by measurement on the various headings.

An analysis of the results indicate the following:

- The coefficient A indicates with 4° an abnormal misalignment of the lubbers line of the compass along the longitudinal axis of the vessel which should be corrected.

- Since deviation is east on headings 090° and west on 000°, it is probable that the south pole of the vessels permanent field is on the port bow.

- Since the deviation on heading 270° is nearly the same as that on 090°, but of opposite sign, adjustment on one of these headings should result in nearly correct adjustment on the other.

The various components and the total deviation are shown in graphical form in figure 2112.

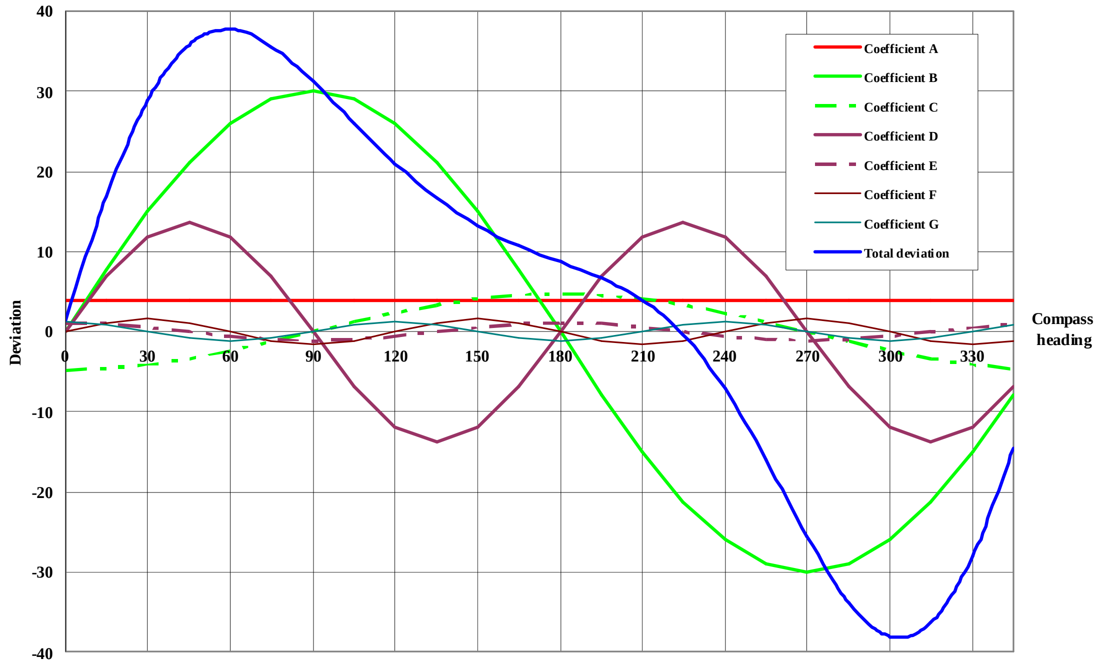


Figure 2112 Coefficients and total deviation of an unadjusted magnetic compass

PART 2

(Terrestrial navigation)

Chapter 2

(Dead Reckoning)

2210 Dead reckoning form and plots

Dead reckoning **(DR)** is the determination of position by advancing a known position for courses and distances. It is reckoning to something stationary or "dead" in the water and hence applies to courses and speeds *through the water*. Because of leeway due to wind, inaccurate allowance for compass error, imperfect steering, or error in measuring speed, the actual motion through the water is seldom determined with complete accuracy. In addition, if the water itself is in motion, the course and speed over the bottom differ from those through the water.

If the navigator possesses information regarding current, wind, etc., he should use this information, bearing in mind, that applying information of uncertain accuracy may introduce additional error.

Although of less than the desired accuracy, dead reckoning is the only method by which a position can be determined at any time and therefore might be considered *basic navigation,* with all other methods only appendages to provide means for correcting dead reckoning. Dead reckoning not only provides means for continuously establishing an approximate position, but also is of assistance in determining times of Sunrise and Sunset, the celestial bodies available for observation, the predicted availability of electronic aids to navigation, the suitability and interpretation of soundings for checking position, the predicted times of making landfalls or sighting lights, estimates of arrival times, and in evaluating the reliability and accuracy of position determining information.

Because of the importance of accurate dead reckoning, a careful log is kept of all courses and speeds, times of all changes, compass errors, and corrective factors applied for wind and current. Navigators are advised to keep their dead reckoning by plotting directly on the chart or plotting sheet, drawing lines to represent the direction (**Rhumb line)** and distance of travel and indicating dead reckoning positions from time to time.

In order to be able to maintain a clean and comprehensive dead reckoning plot, navigators are advised to use a dead reckoning form as exhibited in figure 2210a below. The dead reckoning form must always be kept up to date and shall contain all information required to calculate the vessel's true curse (RwK), like magnetic compass curse (MgK), compass deviation at the vessel's compass curse, and the variation applicable to the sailing area. If information is available for wind leeway (Bw), and current drift and set it should be used to calculate the vessels curse over ground (COG) and speed over ground (SOG).

Date	Time	Log	Distance [Sm]		CH	Deviation	MH	Variation	RwK	Bw Wind	KdW in	> Current	COG	FdW	SOG	Current	
		[Sm]	Actual	Cum	[°]	[°]	[°]	[°]	[°]	[°]	[°]	[°]	[°]	[Kn]	[Kn]	Drift [Kn]	Set [°]

Figure 2210a Dead reckoning form

Figure 2210b below exhibits a typical dead reckoning plot.

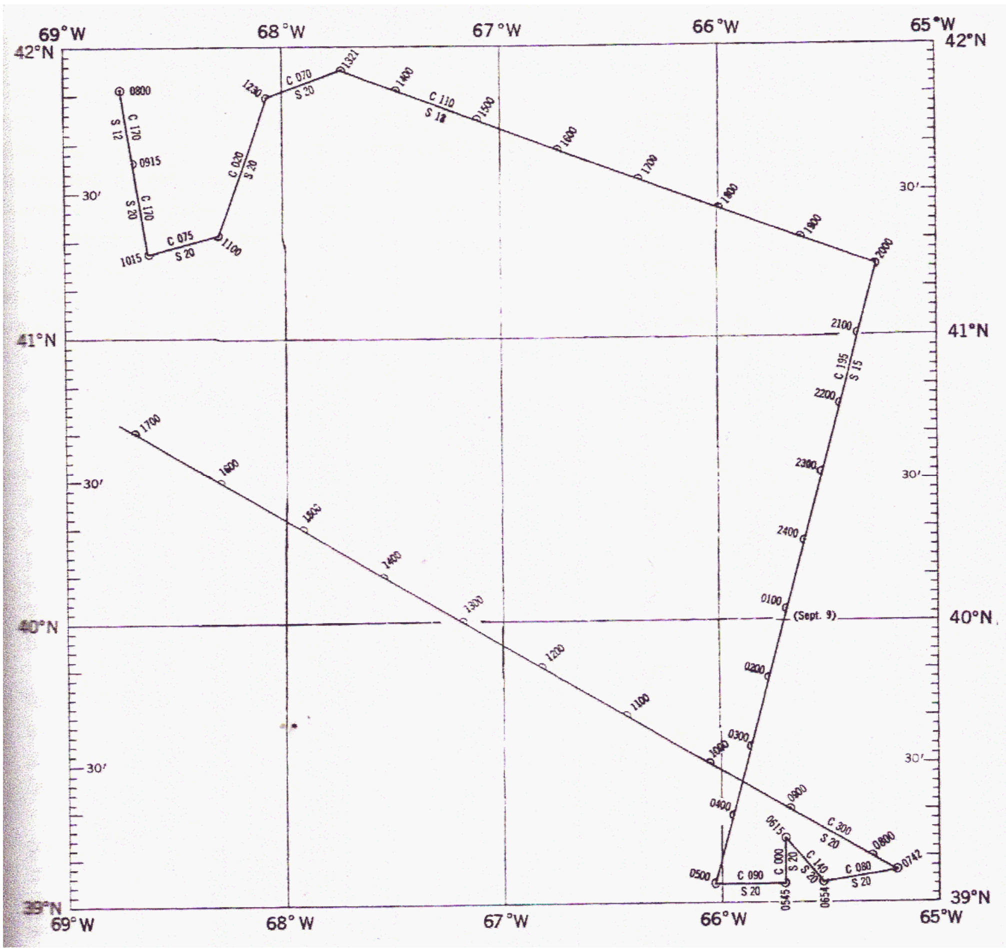


Figure 2210b Typical dead reckoning plot

Example: *A sailing vessel is sailing with a south westerly wind of 6 Bf through a current having a set of 040° and a drift of 1,5 Kn. The vessel is on 175° compass curse (MgK) and its speed through the water (FdW) is 6,5 Kn. The estimated wind leeway is Bw=6°W. The compass deviation is 6°W and the variation in the sailing area is 3,2°E. Required: Use the dead reckoning form exhibited in figure 2210a, and the current triangle as shown in figure 2540 to answer the following questions. 1) Magnetic heading (MwK). 2) True curse (RwK). 3) Curse through the water (KdW). 4) Speed over Ground (SOG). 5) Current leeway (β). 6) Curse over ground (COG)*

Answer: ***1) MwK = MgK + Deviation =175-6=169°***

2) RwK = Mwk + Variation =169+3,2=172,2°

3) KdW = RwK + Bw =172,2-6=166,2°

4) set + (180°-KdW) +(180°- φ) = 180°

φ = 180 – (KdW – set) = 180 – (166, 2 – 40) = 53, 8°

$$SOG = \sqrt{FdW^2 + drift^2 - 2 * FdW * drift * \cos\varphi}$$

SOG = $\sqrt{6{,}5^2 + 1{,}5^2 - 2 * 6{,}5 * 1{,}5 * \cos 53{,}8°}$ **= 5, 7 Kn**

5) $\dfrac{SOG}{\sin\varphi} = \dfrac{drift}{\sin\beta}$; $\beta = \arcsin(\dfrac{drift}{SOG}\sin\varphi)$; $\beta = \arcsin(\dfrac{1{,}5}{5{,}7} * \sin 53{,}8°)$

β= 12, 3° W

6) COG = KdW + β = 166,2 – 12,3 = 154°

PART 2

(Terrestrial navigation)

Chapter 3

(The sailings)

2310 General

Dead reckoning involves the determination of one's present or future position by projecting the ship's course and distance run from a known position. A closely related problem is that of finding the course and distance from one known point to another known point. For short distances, these problems are easily solved directly on charts, but for long distances, a purely mathematical solution is often a better method. Collectively, these methods are called the sailings.

2320 Rhumb line and great circles

The principal advantage of a Rhumb line is that it maintains constant true direction. A ship following the Rhumb line between two places does not change true course. A Rhumb line makes the same angle with all meridians it crosses and appears as a straight line on a Mercator chart. For any other case, the difference between the Rhumb line and the great circle connecting two points increases (1) as the latitude increases, (2) as the difference of latitude between the two points decreases, and (3) as the difference of longitude increases.

On a Mercator chart a great circle appears as a sine curve extending equal distances each side of the equator. The Rhumb line connecting any two points of the great circle on the same side of the equator is a chord of the curve. Along any intersecting meridian the great circle crosses at higher latitude than the Rhumb line. If the two points are on opposite sides of the equator, the direction of curvature of the great circle relative to the Rhumb line changes at the equator. The Rhumb line and great circle may intersect each other, and if the points are equal distances on each side of the equator, the intersection takes place at the equator.

Since great circles other than a meridian or the equator are curved lines whose true direction changes continually, the navigator does not attempt to follow it exactly. Rather, he selects a number of points along the great circle, constructs Rhumb lines between the points, and follows these Rhumb lines from point to point.

2330 Kinds of sailings

There are different kinds of sailings.

- **Great circle sailing** involves the solution of courses, distances, and points along a great circle between two points.

- **Plane sailing** solves problems involving a single course and distance, difference of latitude, and departure, in which the Earth is regarded as a plane surface. This method, therefore, provides solution for latitude of the point of arrival, but not for the longitude. To calculate the longitude, the spherical sailings are necessary. Do not use this method for distances of more than a few hundred miles.

- **Parallel sailing** is the Interco version of departure and difference of longitude when a vessel is proceeding due east or due west. This method is seldom used.

- **Traverse sailing** combines the plane sailing solutions when there are two or more courses and determines the equivalent course and distance made good by a vessel steaming along a series of Rhumb lines.

- **Middle- (or mid-) latitude sailing** uses the mean latitude for converting departure to difference of longitude when the course is not due east or due west.

2340 Terms and definitions

In solutions of the sailings, the following quantities are used:

- **Latitude (φ)**. The latitude of the point of departure is designated **φ1**; that of the destination, **φ2**; middle (mid) or mean latitude, **φm**; latitude of the vertex of a great circle, **φv**; and latitude of any point on a great circle, **φx**.

- **Mean latitude (φm)**. Half the arithmetical sum of the latitudes of two places on the same side of the equator.

- **Difference of latitude (Δφ)**.

- **Longitude (λ)**. The longitude of the point of departure is designated **λ1**; that of the point of arrival or the destination, **λ2**; of the vertex of a great circle, **λv**; and of any point on a great circle, **λx.**

- **Difference of longitude (Δλ)**.

- **Distance (D)**.

- **Course** or **course angle (Cn or C)**.

- **Departure (p)**.

2350 Great circle sailing

The intersection of a plane and the surface of a sphere is a circle, a great circle if the plane passes through the centre of the sphere. The arc of a great circle on the surface of the Earth passing through two geographic locations represents the shortest sailing distance between said locations.

Since a great circle is continuously changing direction as one proceeds along it, no attempt is customarily made to follow it exactly, except in Polar Regions. Rather, a number of points are selected along the great circle, and Rhumb lines are followed from point to point, taking advantage of the fact that for short distances a great circle and a Rhumb line almost coincide. The number of points to be used is a matter of preference, but as general rule, each 5° of longitude is a convenient length. Legs of equal length are not provided in this way, but this is not objectionable under normal conditions. If a magnetic compass is used, the variation for the middle of the leg is used for the entire leg.

Land, ice, or severe weather may prevent the use of great circle sailing for some or all of one's route. It is therefore important to calculate and plot in the chart the position of the great circle vertex, which provides information about the highest latitude of the intended route, and to check for any hazards on both sides of the vertex. If the great circle route crosses a navigation hazard, change the track. It may be satisfactory to follow a great circle to the vicinity of the hazard, one or more rhumb lines along the edge of the hazard, and another great circle to the destination. Still another is the use of two great circles, one from the point of departure to a point near the maximum latitude of unobstructed water and the second from this point to the destination.

2351 Finding the Distance and the initial course

In Figure 2351 below, 1 is the point of departure, 2 the destination, Pole the pole near 1, 1/X/V/2 the great circle through 1 and 2, V the vertex, and X a point on the great circle.

- The arcs B and P are the colatitudes of the point of departure $(90 - \varphi 1)$ and the point of destination $(90 - \varphi 2)$ respectively. If 1 and 2 are on opposite sides of the equator P is $(90 + \varphi 2)$.
- The length of arc Z is the great circle distance between 1 and 2.
- The angle at 1 which in the celestial triangle is the azimuth (Az) of the body S, represents on the Earth surface the initial great circle course from 1 to 2.
- The angle at the pole which in the celestial triangle is the local hour angle (LHA) of the body S, represents on the Earth surface the difference in longitude between the meridian of the destination and that of the departure $\Delta\lambda = \lambda 2 - \lambda 1$.

Solving the spherical great circle triangle of Figure 2351 below, as already demonstrated for the celestial triangle (Ref. § 3440 below), one gets the following equations:

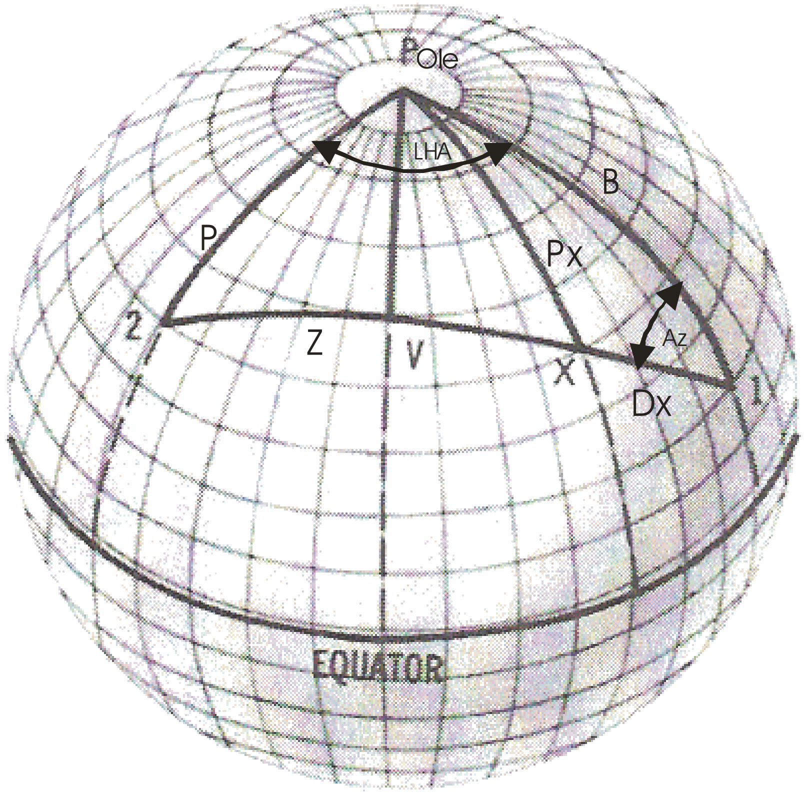


Figure 2351 The navigational triangle and great circle sailing

Great circle distance: $D = \arccos(\cos\varphi 1 * \cos\varphi 2 * \cos\Delta\lambda + \sin\varphi 1 * \sin\varphi 2)$

Initial course angle: $C = arctg \dfrac{\sin\Delta\lambda}{\cos\varphi 1 * tg\varphi 2 - \sin\varphi 1 * \cos\Delta\lambda}$ ⟶ Cn = $\begin{matrix} N & & E \\ & \{C\} & \\ S & & W \\ \uparrow & & \uparrow \\ \varphi 1 & & \Delta\lambda \end{matrix}$

Rules for computation of D and C.

- When $\varphi 1$ and $\varphi 2$ are of contrary name $\varphi 2$ is treated as a negative quantity.
- When C is negative, the reference from which Cn starts counting has a name contrary to the name of the latitude of departure.
- Cn is counting from its north or south reference to the amount defined by C to an east or west direction depending on the name of $\Delta\lambda$.

Example 1: *Find the distance and the initial great circle course from latitude 32°S, longitude 116°E to latitude 30°S, longitude 31°E.*

Answer: *D=arccos[cos32*cos30*cos(116-31)+sin32*sin30]=70,79°*60=* ***<u>4.247,5 Sm</u>***

$$C = arctg \frac{\sin(116-31)}{\cos 32 * tg30 - \sin 32 * \cos(116-31)} = 66$$; **<u>Cn=S66W=246°</u>**

Example 2: *Find the distance and the initial great circle course from latitude 38°N, longitude 122°W to latitude 24°S, longitude 151°E.*

Answer: *D=arccos[cos38*cos(-24)*cos[(360-(122+151)]+sin38*sin(-24)= 102,28°*60 =* ***<u>6.137 Sm</u>***

$$C = arctg \frac{\sin[360-(122+151)]}{\cos 38 * tg(-24) - \sin 38 * \cos[360-(122+151)]} = (-)69$$;

<u>Cn=S69W=249°</u>

2352 Finding the distance from the point of departure to the vertex

The vertex of a great circle track is the point of the maximum latitude of the route. Severe weather, land or other expected navigation hazards may prevent the use of great circle sailing for some or the entire route. It is therefore for routes following great circle tracks important to know the vertex of the route in order be able to check for potential obstructions.

The latitude of the destination can be calculated solving the following equation for the spherical triangle of Figure 2321:

cosP=cosB*cosZ+sinB*sinZ*cosAz

Using the definitions provided in §2351 above one gets:

$$(1) \quad \sin\varphi 2 = \sin\varphi 1 * \cos D + \cos\varphi 1 * \sin D * \cos C$$

With known latitude of departure $(\varphi 1)$ and initial course angle (C), one needs to determine the value of the distance to the vertex (Dv) at which the latitude of the vertex $(\varphi 2)$ in equation (1) above reaches its maximum $(\varphi 2 \max = \varphi v)$.

$$\frac{d \sin\varphi 2}{dDv} = -\sin\varphi 1 * \sin Dv + \cos\varphi 1 * \cos Dv * \cos C = 0$$

Distance of the point of departure to the vertex: $Dv = arctg \frac{\cos C}{tg\varphi 1}$

2353 Finding the latitude of the vertex

The latitude of the vertex, φv, is always numerically equal to or greater than φ1 or φ2. If the initial course angle, C, is less than 90°, the nearer vertex is towards φ2, but if C is greater 90°, the nearer vertex is in the opposite direction. The vertex nearer φ1, has the same name as φ1.

Replacing sinD and cosD in equation (1) of §2352 by the tangents of the same angle D, one gets the following expression:

$$\sin\varphi 2 = \sin\varphi 1 * \frac{1}{\sqrt{1+tg^2 D}} + \cos\varphi 1 * \frac{tgD}{\sqrt{1+tg^2 D}} * \cos C$$

Substituting the distance D in the above equation by the distance of the point of departure to the vertex (Dv) determined in §2352 above, the latitude of destination ($\varphi 2$) becomes the latitude of the vertex (φv).

Latitude of the vertex: $$\varphi v = \arcsin\frac{\sin\varphi 1 + \cos\varphi 1 * \cos C * tgDv}{\sqrt{1+tg^2 Dv}}$$

2354 Finding the difference of longitude of the vertex and the point of departure ($\Delta\lambda$)

At the vertex the initial course angle to the point of destination is either 90° or 270°, which means that the tangents of the initial course equation as defined in §2351 above becomes in both cases infinitive. This is only possible if the denominator of said equation becomes zero, i.e. if:

$$\cos\varphi 1 * tg\varphi 2 - \sin\varphi 1 * \cos\Delta\lambda = 0 \quad \text{respectively} \quad \cos\varphi v * tg\varphi 2 = \sin\varphi v * \cos(\lambda 2 - \lambda v)$$

This equation provides a solution for the difference in longitude between the vertex and the point of destination. Replacing ($\varphi 2$) by ($\varphi 1$) leads to the requested formula for $\Delta\lambda = \lambda 1 - \lambda v$.

Difference of longitude of the vertex and the point of departure: $$\Delta\lambda = \arccos\frac{tg\varphi 1}{tg\varphi v}$$

Example: *Find the distance, the latitude and the longitude of the vertex of the great circle track from latitude 38°N, 125°W when the initial great circle course angle is N69°W.*

Answer: $Dv = arctg\frac{\cos(360-69)}{tg38}$ *= 24,64°*60=* ***<u>1.478 Sm</u>***

$$\varphi v = \arcsin\frac{\sin 38 + \cos 38 * \cos(360-69) * tg24{,}64}{\sqrt{1+tg^2 24{,}64}}$$ = 42,64°=***<u>42° 38,4 N</u>***

$$\lambda v = \lambda 1 + \arccos \frac{tg 38}{tg 42{,}64} = 125° + 31{,}95° = \underline{\mathbf{157°W}}$$

2355 Navigating along the great circle track

Having determined the initial great circle course **(C)**, the distance to the destination **(D)**, the latitude and longitude of the great circle vertex **(φv / λv)** and the distance from the point of departure to the vertex **(Dv)**, the navigator sails from the point of departure along a Rhumb line with the course C until it reaches, with reference to the longitude of departure, a difference in longitude of **Δλx = 5°.**

Point X on Figure 2351 represents the end of the first Rhumb line leg. Its position is defined by **φx / λx,** and its distance from the point of departure is **Dx** . Solving the spherical triangle Dx/Px/B of Figure 2351 above as already demonstrated for the celestial triangle (Ref. §3412 below) one gets the following equations.

cosDx = cosPx*cosB + sinPx*sinB*cosΔλx
cosDx = cos(90- φx)*cos(90-φ1) + sin(90-φx)*sin(90-φ1)*cosΔλx

(1) cosDx = cos φx*cos φ1*cosΔλx + sin φx*sin φ1

$$\frac{\sin Dx}{\sin \Delta\lambda x} = \frac{\sin Px}{\sin C} = \frac{\sin(90 - \varphi x)}{\sin C} = \frac{\cos \varphi x}{\sin C}$$

$$(2) \qquad \sin Dx = \sin \Delta\lambda x * \frac{\cos \varphi x}{\sin C}$$

cosPx = cosB*cosDx + sinB*sinDx*cosC
cos(90 - φx) = cos(90 - φ1)*cosDx + sin(90 - φ1)*sinDx*cosC

(3) sin φx = sinDx*cos φ1*cosC + cosDx*sin φ1

Substituting in equation (3) sinDx by equation (2) and cosDx by equation (1) above, one gets for the end of the first leg the following solution for the latitude of this leg:

$$\varphi x = arctg \frac{\sin \varphi 1 * \cos \Delta\lambda x + ctgC * \sin \Delta\lambda x}{\cos \varphi 1}$$

The distance of the end of the first leg from the point of departure can be calculated in accordance with the rules explained for the mean latitude sailing in §2370 below.

Example: *The captain of a vessel with an actual position 37°N / 125°W wishes to sail to the position 25°S / 150°E, following a great circle track. Required: 1) the distance and the great circle course. 2) the distance from the point of departure to the vertex. 3) Latitude and longitude of the vertex. 4) The latitude of the end of the first leg and its distance from the point of departure. 5) Initial course and distance of the great circle from the end of the first leg to the point of destination.*

Answer: *1) D = [arcos(cosφ1*cosφ2*cosΔλ + sinφ1*sinφ2)]*60*

*D ={ arcos[cos37*cos(-25)*cos[360-(125+150)] + sin37*sin(-25)]}*60*

<u>D = 6.061 Sm</u>

$$C = arctg\frac{\sin\Delta\lambda}{\cos\varphi 1 * tg\varphi 2 - \sin\varphi 1 * \cos\Delta\lambda}$$

$$C = arctg\frac{\sin[360-(125+150)]}{\cos 37 * tg(-25) - \sin 37 * \cos[360-(125+150)]} = -66{,}9°$$

<u>Cn = S66,9W = 247°</u>

$$2)\ Dv = arctg\frac{\cos C}{tg\varphi 1} = [arctg\frac{\cos(-66{,}9)}{tg 37}] * 60 = 27{,}5037 * 60$$

<u>Dv = 1.650 Sm</u>

$$3)\quad \varphi v = \arcsin\frac{\sin\varphi 1 + \cos\varphi 1 * \cos C * tgDv}{\sqrt{1+tg^2 Dv}}$$

$$\varphi v = \arcsin\frac{\sin 37 + \cos 37 * \cos(-66{,}9) * tg 27{,}5037}{\sqrt{1+tg^2 27{,}5037}} = 42{,}7237°\ N$$

<u>φv = 42° 43,4´N</u>

$$\Delta\lambda v = \arccos\frac{tg\varphi 1}{tg\varphi v} = \arccos\frac{tg 37}{tg 42{,}7237} = 35{,}3193°W$$

<u>λv = λ1 + Δλ =125 + 35,3193 = 160° 19,2´ W</u>

$$4)\quad \varphi x = arctg\frac{\sin\varphi 1 * \cos\Delta\lambda x + ctgC * \sin\Delta\lambda x}{\cos\varphi 1}$$

$$\varphi x = arctg\frac{\sin 37 * \cos 5 + ctg(-66{,}9) * \sin 5}{\cos 37} = 35{,}1497°\ N$$

<u>φx = 35° 9´N</u>

φm = (φ1 + φx)/2 = (37 + 35,1497)/2 = 36,0749° N

$$Dx = \frac{\Delta\lambda x * \cos\varphi m * 60}{\sin C} = \frac{5 * \cos 36{,}0749 * 60}{\sin 66{,}9} = 263{,}6$$

<u>Dx = 264 Sm</u>

*5) Dx2 = {arcos[cos35,1497*cos(-25)*cos[360-(120+150)]*
*+ sin35,1497*sin(-25)]}*60*

<u>Dx2 = 5.795 Sm</u>

$$Cx2 = arctg\frac{\sin[360-(120+150)]}{\cos 35{,}1497 * tg(-25) - \sin 35{,}1497 * \cos[360-(120+150)]}$$

= -63,9796

<u>Cnx2 = S64W = 244°</u>

2360 Traverse sailing

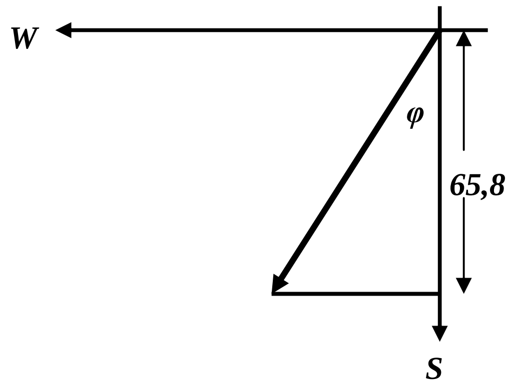
A traverse is a series of courses or a track consisting of a number of course lines, such as might result from a sailing vessel beating into the wind. Traverse sailing is the finding of a single equivalent course and distance.

Example: *A ship steams as follows: course 158°, distance15.5 Sm; course 135°, distance 33.7 Sm; course 259°, distance 16.1 Sm; course 293°, distance 39.0 Sm; course 169°, distance 40.4 Sm. Required: Equivalent single (1) course (2) distance.*

Solution: *Solve each leg as a plane sailing to obtain the difference in latitude and the departure, label the difference in latitude and the departure values N, S, W, or E as appropriate and tabulate the results as follows:*

Course	***Distance***	***Difference in latitude***		***Departure***	
[C]	***[D]***	***[N]***	***[S]***	***[E]***	***[W]***
[°]	***[Sm]***	***[Sm]***	***[Sm]***	***[Sm]***	***[Sm]***
158	*15,5*		*14,4*	*5,8*	
135	*33,7*		*23,8*	*23,8*	
259	*16,1*		*3,1*		*15,8*
293	*39,0*	*15,2*			*35,9*
169	*40,4*		*39,7*	*7,7*	
Subtotals		*15,2*	*81,0*	*37,3*	*51,7*
Correction			*-15,2*		*-37,3*
Totals			***65,8***		***14,4***

*Thus, the latitude difference is **S 65,8 Sm** and the departure is **W 14,4 Sm**. Convert this to a course and distance using the formulas exhibited below.*



Answer: ***(1) C = S φ W = S * arctg(14,4/65,8) W = 192,3°***

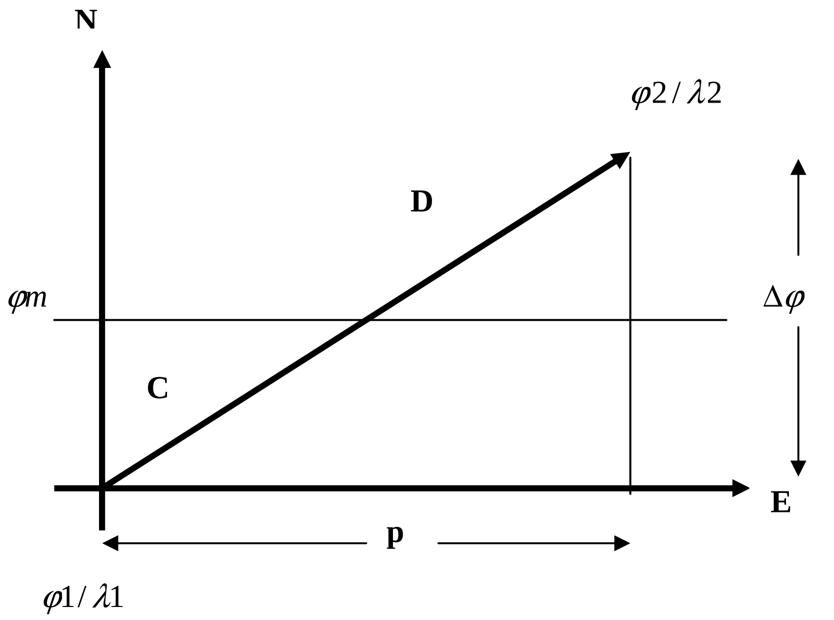
(2) $D = \sqrt{65{,}8^2 + 14{,}4^2}$ ***= 67,4 Sm.***

2370 Mean latitude sailing

Mean latitude sailing combines plane sailing and parallel sailing. Plane sailing is used to find difference of latitude and departure when course and distance are known, or vice versa. Parallel sailing is used to interconvert departure and difference of longitude.

The mean latitude (**φm**) is half the arithmetical sum of the latitudes of two places on the same side of the equator. It is labelled N or S to indicate its position north or south of the equator. If a course line crosses the equator, solve each course line segment separately.

Example 1: *A vessel steams 1.253 Sm on course 070° from lat. 15°17,0' N, long. 151°37,0' E. Required: Latitude and longitude of the point of arrival.*



Answer: *The difference in latitude can be calculated as follows:*

$$\Delta\varphi = \frac{D * \sin(90° - C)}{60} = \frac{1.253 * \sin(90° - 70)}{60} = 07°\ \ 8{,}6'N$$

The latitude of arrival is therefore: $\varphi 2 = \varphi 1 + \Delta\varphi$

φ2= 22° 25, 6´ N

*The departure **(p)** can be calculated as follows:*

p=D cos(90° - C) = 1.253*cos(90° - 70) = 1.177,5 Sm*

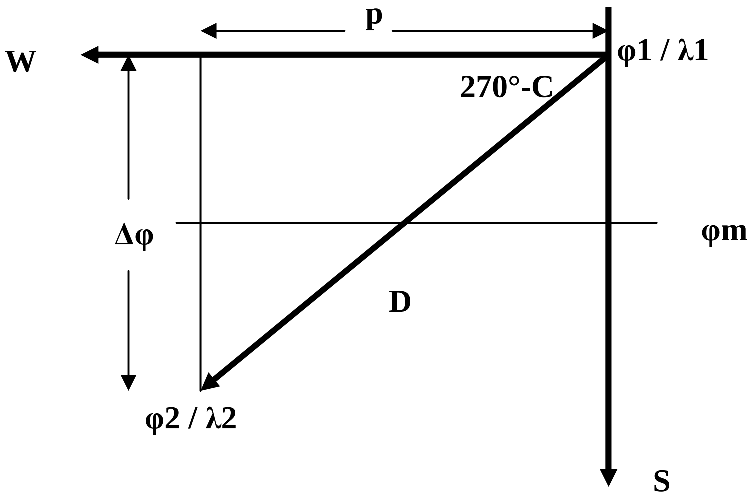
With φm = φ1 + Δφ/2 = 15,2883° +7,1433°/2 = 18,86°
The difference in longitude can be calculated as follows:

$$\Delta\lambda = \frac{p}{60 * \cos\varphi m} = \frac{1.177{,}5}{60 * \cos 18{,}86°} = 020°\ \ 44{,}3'\ E$$

The longitude of arrival is therefore: λ2 = λ1 + Δλ

λ2 = 172° 21,3´ E

Example 2: *A vessel at latitude 08° 48,9´S, longitude 089° 53,3´W is to proceed to latitude 17° 06,9´S, longitude 104° 51,6´W. Required: Course and distance.*



Answer: *The difference in latitude is:* $\Delta\varphi=\varphi 2-\varphi 1=17{,}115°-8{,}815° = 8{,}3° \equiv 498$ *Sm*

With $\boldsymbol{\varphi m} = \varphi 1 + \Delta\varphi/2 = 8{,}815° + 8{,}3°/2 = 12{,}965°$, *and the difference in longitude* $\Delta\lambda=\lambda 2 - \lambda 1=104{,}86° - 89{,}8883° = 14{,}9717°$, *the departure is:*

$\mathbf{p} = \Delta\lambda * 60 * \cos\varphi m = 14{,}9717 * 60 * \cos 12{,}965 = 875{,}4$ *Sm.*

The distance to the destination can be calculated as follows:

$$D=\sqrt{\Delta\varphi^2+p^2}=\sqrt{498^2+875{,}4^2}=\sqrt{248.004+766.325}$$

D = 1.007,1 Sm

The course to the destination can be calculated as follows:

$C = 270° - arctg(\Delta\varphi/p) = 270 - arctg(498/875{,}4) = 270 - arctg(0{,}5689)$

C = 240,4°

PART 2

(Terrestrial navigation)

Chapter 4

(Piloting)

2410 General

On the high seas, where there is no immediate danger of grounding, navigation is a comparatively leisurely process. Courses and speeds are maintained over relatively long periods, and fixes are obtained at convenient intervals. Errors in position can usually be detected and corrected before danger threatens.

In the vicinity of shoal water where frequent changes of course and speed are common the situation is different. Frequent or continuous positional information is usually essential to the safety of the vessel. No other form of navigation requires the continuous alertness needed in piloting. At no other time navigational experience and judgment is so valuable. The ability to work rapidly and to correctly interpret all available information, always keeping “ahead of the vessel,” may mean the difference between safety and disaster.

2420 Lines of position

A line of position **(LOP)** is one on some point of which the vessel may be presumed to be located, as a result of observation or measurement. It may be highly reliable, or of questionable accuracy. Lines of position are of great value, but one should always keep in mind that they can be in error because of imperfections in instruments used to obtain them and human limitations in those who use the instrument and utilize the results. The extent to which one can have confidence in various lines of position is a matter of judgement acquired from experience.

A line of position might be a straight line (actually a part of a great circle), an arc of a circle, or part of some other curve. An appropriate label should be placed on the plot of a line of position at the time it is drawn, to avoid possible error or confusion. A label should include all information essential for identification, but no more than that.

2430 Types of fixes

While the intersection of two LOP’s constitutes a fix the prudent navigator will always use at least three LOP’s if they are available, so that an error is apparent if they don’t meet in a point. Some of the most commonly used methods of obtaining LOP’s are discussed below:

- **Fix by Bearings:** The navigator can take and plot bearings from two or more charted objects. This is the most common and often the most accurate way to fix a vessel’s position. Bearings may be taken directly to charted objects, or tangents of points of land (Ref. Figure 2430a). The intersection of these lines constitutes a fix. A position taken by bearings to buoys should not be considered a fix, but an estimated position (EP), because buoys swing about their watch circle and may be out of position.

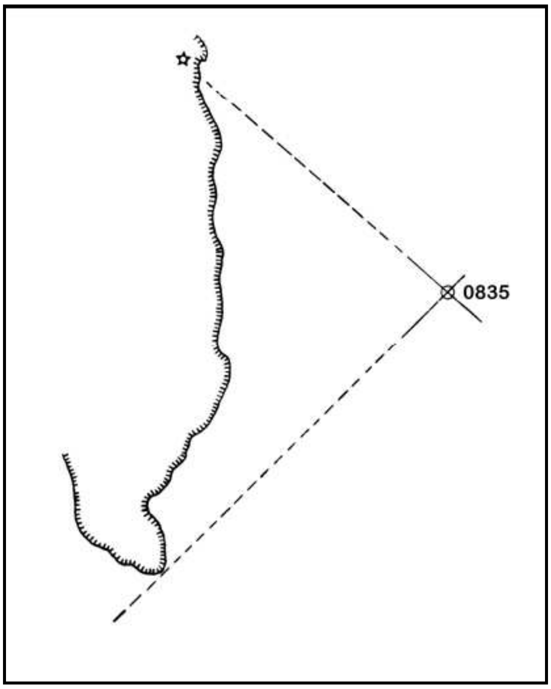


Figure 2430a A fix by two bearing lines

- **Fix by Ranges:** The navigator can plot a fix consisting of the intersection of two or more range arcs from charted objects. He can obtain ranges by radar measurements (Ref. Figure 2430b) or by sextant vertical angles (Ref §2453).

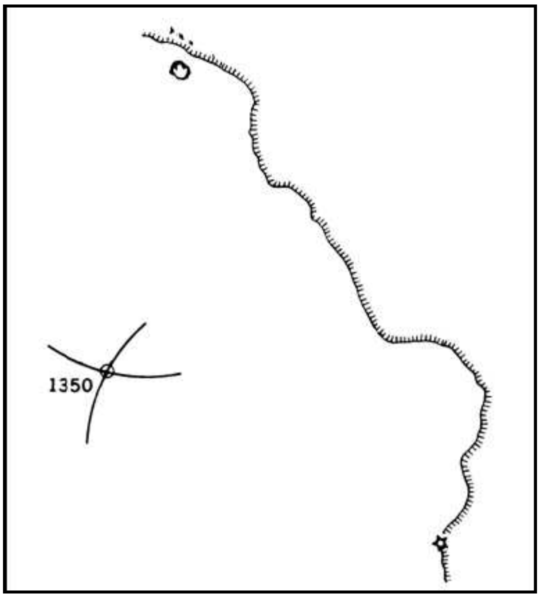


Figure 2430b A fix by two radar ranges

- **Fix by Bearing and Range:** This is a hybrid fix of LOP's from a bearing and range to a single object. The radar is the only instrument that can give simultaneous range and bearing information to the same object. Therefore, with the radar, the navigator can obtain an instantaneous fix from only one NAVAID. This unique fix is shown in Figure 2430c. This makes the radar an extremely useful tool for the piloting team. The radar's characteristics make it much more accurate determining range than determining bearing; therefore, two radar ranges are preferable to a radar range and bearing. Alternatively if the height of the object is known, the distance to the object can be measured by a sextant vertical angle, and the bearing take by a bearing compass.

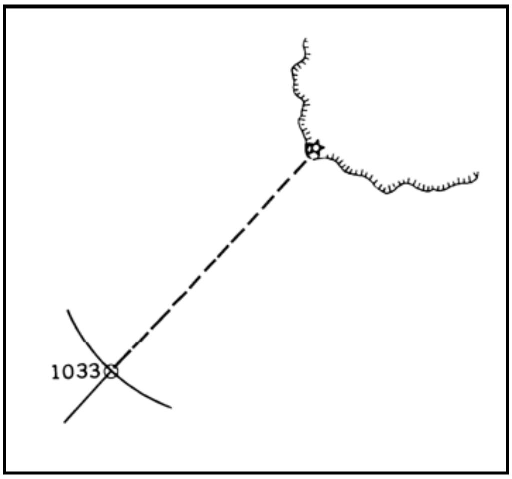


Figure 2430c A fix by range and bearing of a single object

- **Fix by Range Line and Distance:** When the vessel comes in line with a range, plot the bearing to the range and cross this LOP with a distance from another NAVAID. Figure 2430d shows this fix.

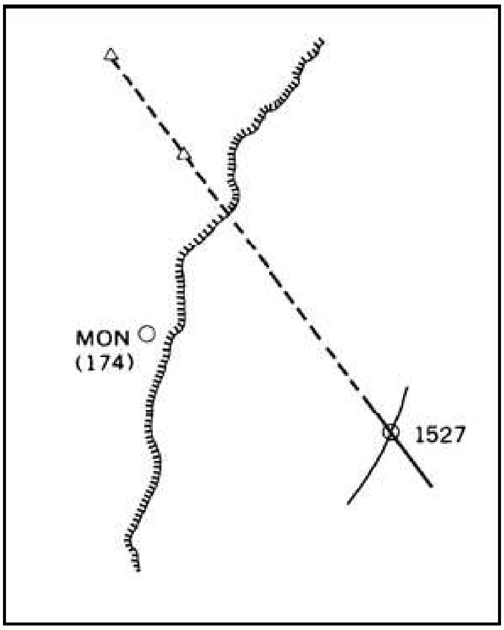


Figure 2430d A fix by the bearing of a range line and the distance of an other object.

2440 The running fix

When only one NAVAID is available from which to obtain bearings, use a technique known as the running fix.

- Plot a bearing to a NAVAID (LOP 1).
- Plot a second bearing to a NAVAID (either the same NAVAID or a different one) at a later time (LOP 2).
- Advance LOP 1 to the time when LOP 2 was taken.

The intersection of LOP 2 and the advanced LOP 1 constitute the running fix.

2441 Advancing a line of position

When advancing a line of position, account for course changes, speed changes, and set and drift between the two bearing lines. Three methods of advancing an LOP are discussed below:

- **Method 1:** Ref. Figure 2441a. To advance the 19 24 LOP to 19 42, first apply the best estimate of set and drift to the 19 42 DR position and label the resulting position point B. Then, measure the distance between the dead reckoning position at 19 24 (point A) and point B. Advance the LOP a distance equal to the distance between points A and B. Note that LOP A'B' is in the same direction as line AB. Label the advanced line of position with both the time of observation and the time to which the line is adjusted.

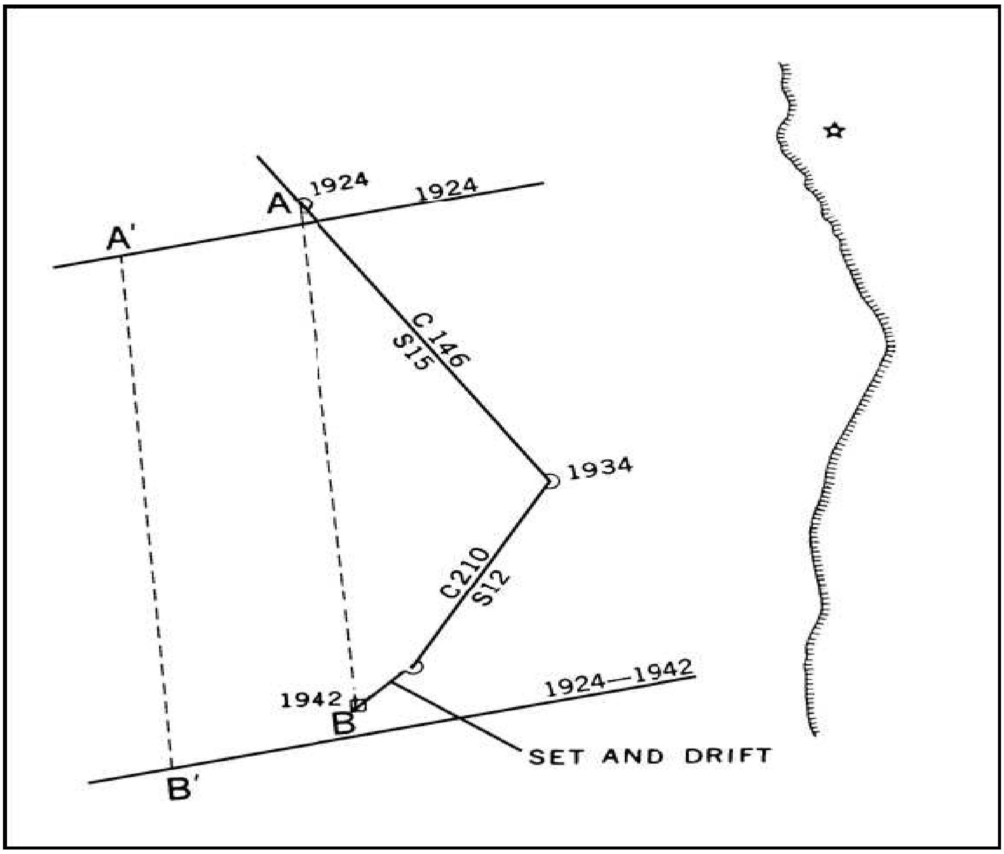


Figure 2441a Advancing a line of position with a change in course and speed, allowing for set and drift.

- **Method 2:** Ref. Figure 2441b. Advance the NAVAIDS position on the chart for the course and distance travelled by the vessel and draw the line of position from the NAVAIDS advanced position. This is the most satisfactory method for advancing a circle of position. Label the advanced line of position with both the time of observation and the time to which the line is adjusted.

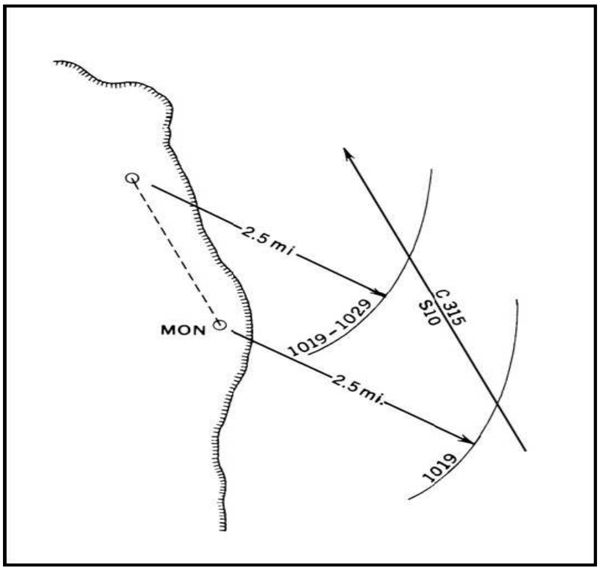


Figure 2441b Advancing a circle of position

- **Method 3:** Ref. Figure 2441c. To advance the 1505 LOP to 1527, first draw a correction line from the 1505 DR position to the 1505 LOP. Next, apply a set and drift correction to the 1527 DR position. This results in a 1527 estimated position (EP). Then, draw from the 1527 EP a correction line of the same length and direction as the one drawn from the 1505 DR to the 1505 LOP. Finally, parallel the 1505 bearing to the end of the correction line as shown. Label the advanced line of position with both the time of observation and the time to which the line is adjusted.

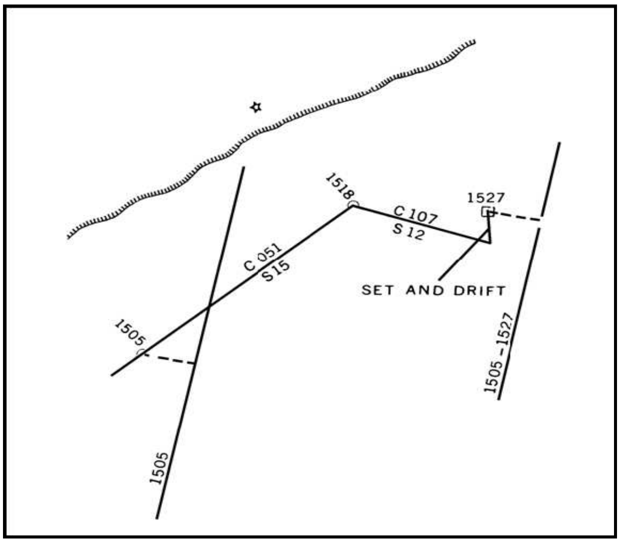


Figure 2441c Advancing a line of position by its relation to the dead reckoning.

2442 Types of running fixes

In the examples below various procedures for obtaining fix positions using running fixes are demonstrated.

- **A running fix by two bearings on the same object.**
  Figure 2442a illustrates the case of obtaining a running fix with no change in course or speed between taking two bearings on the same NAVAID.

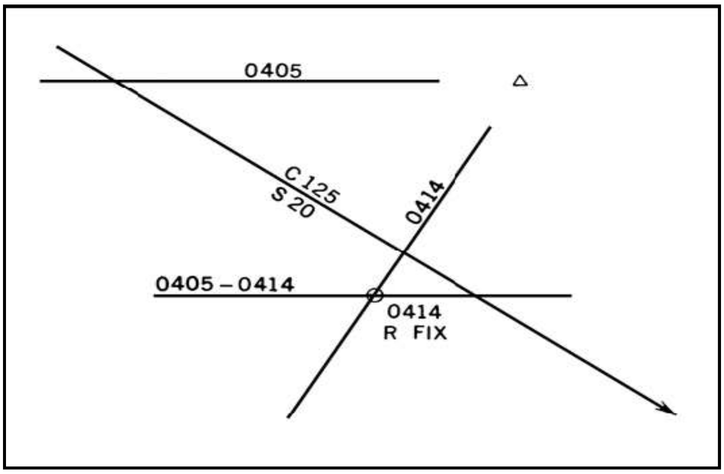


Figure 2442a A running fix by two bearings on the same object

- **Fix by distance of an object by two bearings**
  In a vessel on true course 050° (Ref. Figure 2442b) the navigator takes at A a bearing of the lighthouse D (11 30 LOP). At B he takes a second bearing of the lighthouse D (11 40 LOP) and notes the distance over ground AB made good since the 11 30 observation.

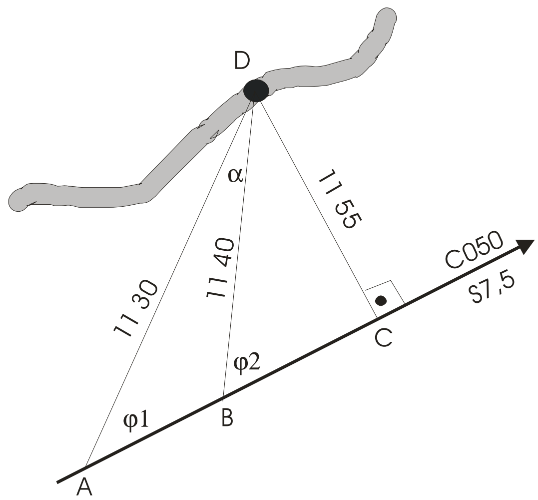


Figure 2442b Fix by distance of an object by two bearings

Using the sinus law explained in §5120 below the navigator can calculate the distance of the vessel from the lighthouse DB and get a fix at 11 40 as follows:

$$DB = \frac{\sin \varphi 1}{\sin(\varphi 2 - \varphi 1)} * AB$$

From the above equation it is obvious that if the vessel proceeds until the bow bearing $\varphi 2$ becomes twice the size of $\varphi 1$, the distance to the lighthouse at 11 40 equals the distance over ground the vessel made good since 11 30. A further specific solution of this type of running fix is obtained if the first observation is made e.g. at 11 40 when $\varphi 2=45°$ and the second at 11 55 when bow bearing of the lighthouse is 90°. In this particular case BC=DC.

- **Fix with changes in a vessel's course and speed between taking two bearings on two different objects.**

Figure 2442c illustrates this procedure using the third method of advancing a line of position.

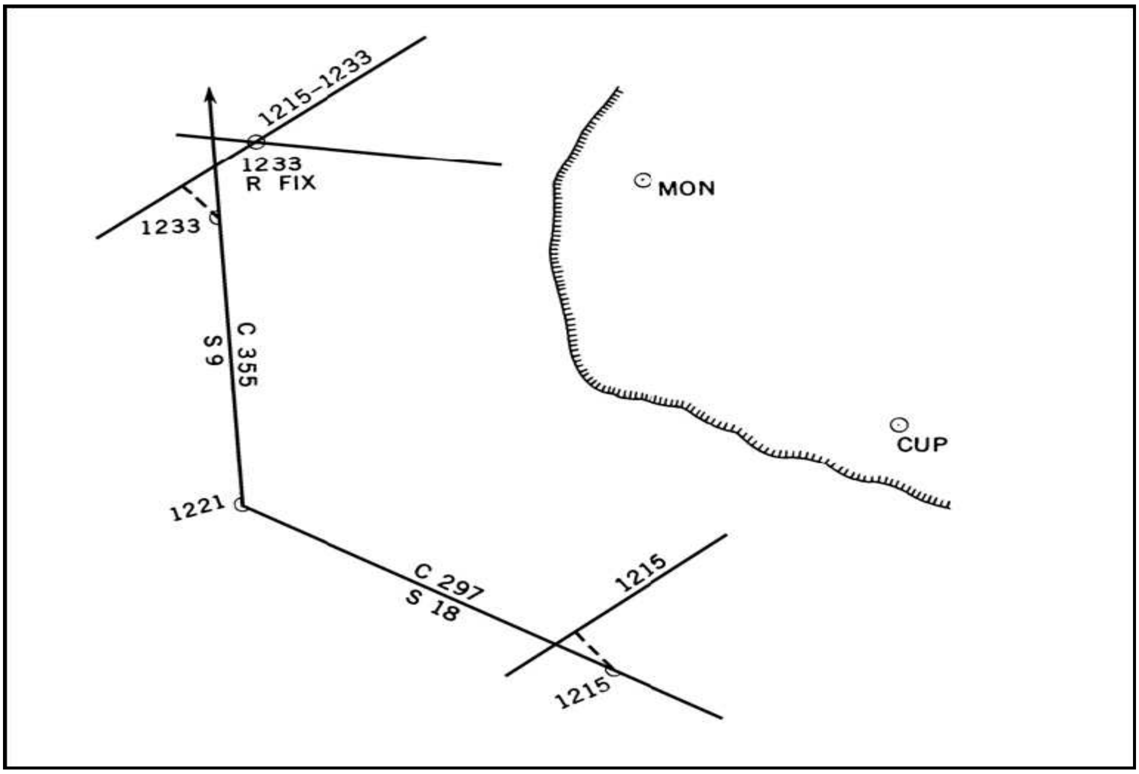


Figure 2442c Fix with changes in a vessel's course and speed between taking two bearings on two different objects.

- **Fix obtained by advancing range circles of position**
  Figure 2442d illustrates a running fix obtained by advancing range circles of position using the second method discussed above.

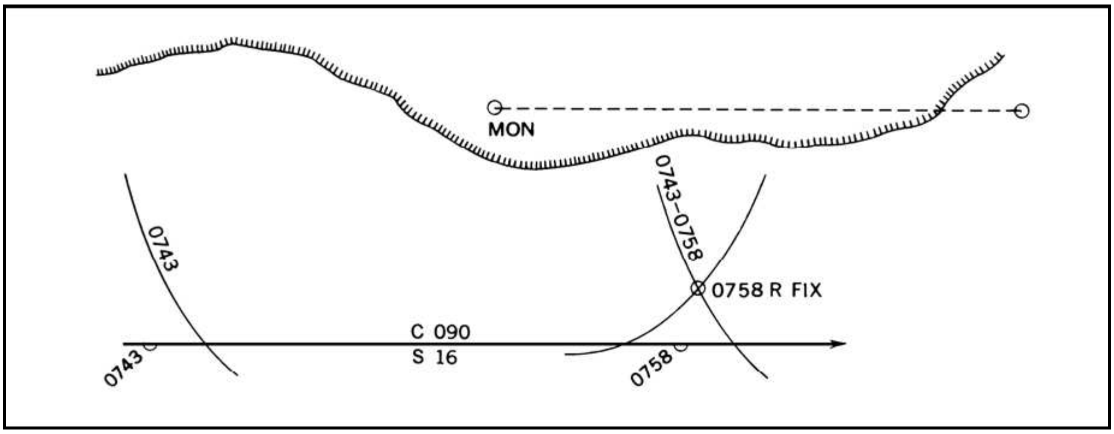


Figure 2442d Fix obtained by advancing range circles of position

2450 Use of sextant in piloting

The marine sextant provides the most accurate means generally available to the mariner for fixing his position in confined waters. The big advantage of the sextant is that it can be used in situations where other methods or tools, including gyro compasses or electronics, are inadequate.

2451 Three point problem

Normally, three charted objects are selected for measuring horizontal sextant angles to determine the observer's position, one of the objects being common to each angular measurement. With nearly simultaneous measurements of the horizontal angles between each pair of charted objects, the observer establishes two circles of position. For each pair of objects there is only one circle which passes through the two objects and the observer's position. Thus there are two circles intersecting at two points as shown in Figure 2451. Since the navigator knows that he is not at the intersection at object 2, the vessels position must be at P.

In plotting the three point fix a procedure is needed to find the centre of each circle of position, some times called **circle of equal angle** and then, about such centre, to strike a arc of radius equal to the distance on the chart from the circle centre to one of the two objects through which the circle passes. The same procedure is applied to the other pair of objects to establish a fix at the intersection of the two arcs.

The centre of each circle of equal angle lies on the perpendicular bisector of the base line of each pair of objects, whilst its length can be calculated by the formulas described in Figure 2451 below.

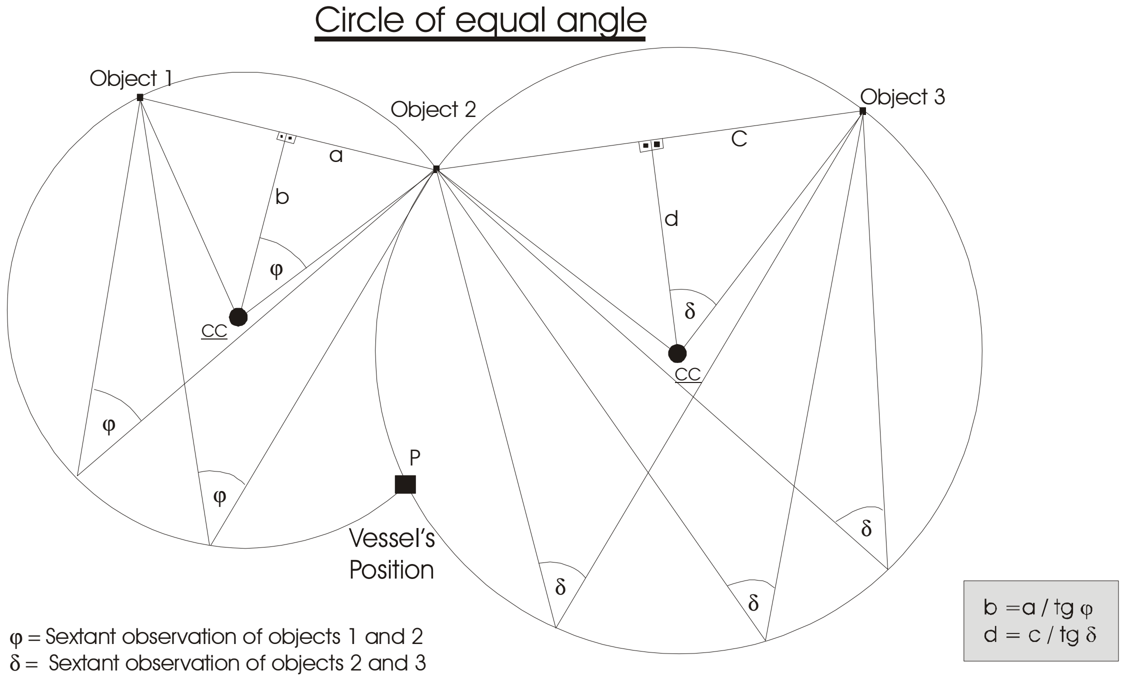


Figure 2451 Solving the three point problem

2452 Horizontal danger angles

A vessel proceeding along a cost may be in safe water as long as it remains a minimum distance off the beach. One method of avoiding particular dangers is the use of **danger angle** as shown in Figure 2452.

A vessel is proceeding along a cost on the indicated course line, and the captain wishes to pass at a safe distance between the dangers A and B. Prominent landmarks are available at C and D.

A circle is drawn through C and D and tangent to the outer edge of the inshore danger A. If Y is a point on this circle, angle **CYD** is the same as at any other point on the circle (except that part between C and D). Anywhere within the circle the angle is **larger** and anywhere outside the circle it is **smaller**. Therefore, any angle smaller than CYD indicates a safe position and any angle larger than CYD indicates a possible danger. Angle CYD is therefore a **maximum horizontal danger angle.**

To keep clear from the offshore danger B a circle is drawn trough C and D and tangent to the inner edge of the danger. If X is a point on this circle, angle **CXD** is the same as at any other point on the circle (except that part between C and D). Anywhere within the circle the angle is **larger** and anywhere outside the circle it is **smaller**. Therefore, any angle larger than CXD indicates a safe position and any angle smaller than CXD indicates possible danger. Angle CXD is therefore a **minimum horizontal danger angle.**

If the vessel is to pass between danger A and B, the horizontal angle between C and D should be kept larger than CYD but smaller than CXD. The minimum danger angle is effective only while the vessel is inside the larger circle trough C and D. Bearings on either landmark might be used to indicate the entering and leaving of the larger circle.

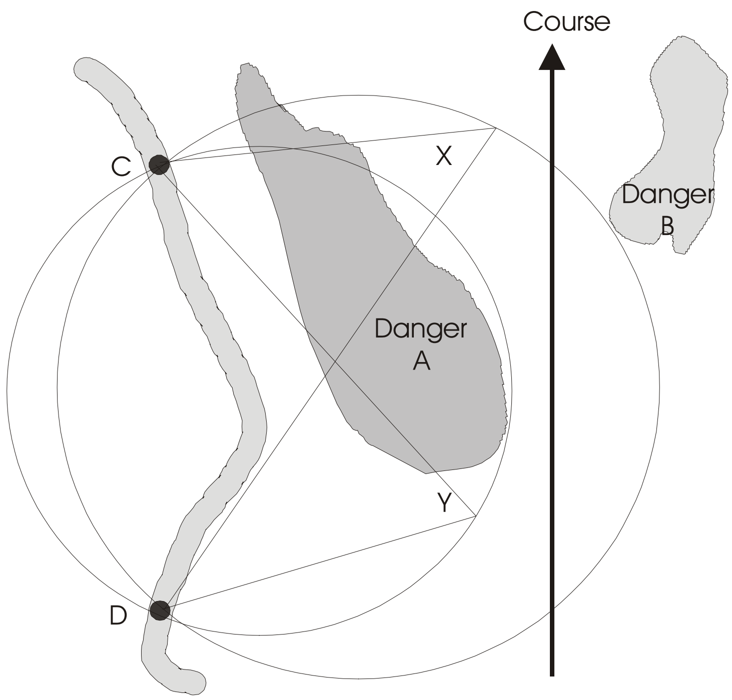


Figure 2452 Horizontal danger angle

2453 Distance by vertical angle

In case an object like a lighthouse is as a hole clear visible from its basis on the sea up to its top, and reliable information reflecting its height is available, a bearing of the lighthouse provides a **L**ine **O**f **P**osition, and its distance to the vessel drawn on the LOP provides the fix.

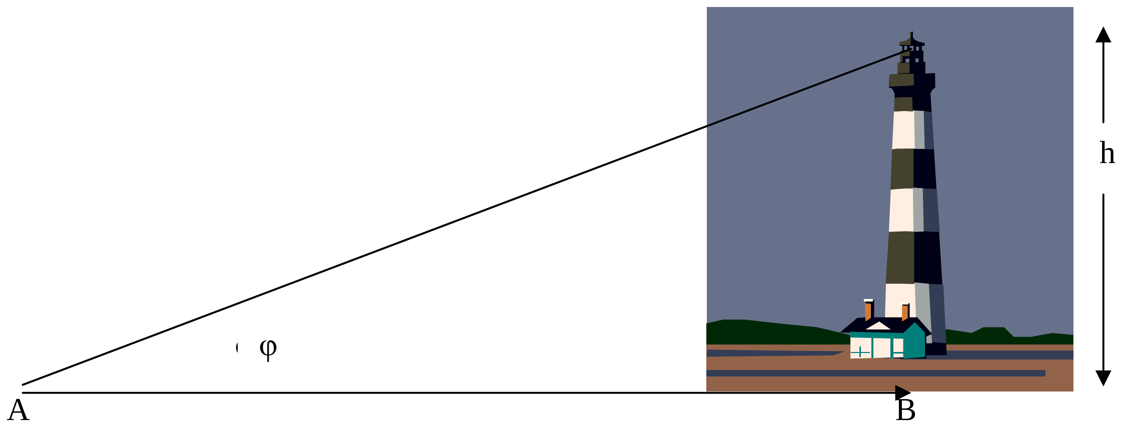


Figure 2453 Fix by sextant vertical angle

The distance AB can be calculated as follows:

$$AB = \frac{h}{tg\varphi}$$

PART 2

(Terrestrial navigation)

Chapter 5

(Tide and current predictions)

2510 Tidal effects

As a general rule, the change in height or the current speed is at first very slow, increasing to a maximum about midway between the two extremes, and than decreasing again.

At high and low water the depth of water is momentarily constant, a condition called ***stand.*** Similarly there is a moment of ***slack water*** as a tidal current reverses its direction. If plotted against time the height of the tide or the speed of the tidal current takes the general form of a cosine square curve.

The ***height of tide*** should not be confused with ***depth of water***. At any time the actual depth is the charted depth plus the height of tide. In most places the reference level is some form of low water. But all low waters at a place are not the same height, and the selected reference level is seldom the lowest tide that occurs at the place. When lower tides occur, these are indicated by a negative sign. It is therefore well to remember that ***the actual depth can be less than the charted depth***.

2520 Tide predictions

Tables with predictions for tides and currents to be expected at various ***reference and subordinate stations*** are published annually by the national authorities. Furthermore the tables include information about the Moon phases at the time of interest enabling the user to decide whether there is spring or neap tide at a specific station. An example of such a table for the calendar year 1977 is given in Fig. 2520a below.

For the ***reference stations*** the time and height of each high and low water are given in chronological order as well as the delay of occurrence of the spring tide at the reference station. Since two high tides and two low tides occur each tidal day, the type of tide at that place is semidiurnal. The tidal day being longer than the civil day (because of the revolution of the Moon eastward around the Earth), any given tide occurs later from day to day. Because of later times of corresponding tides from day to day, certain days have only one high water or only one low water.

For each ***subordinate station*** the following information is given:

- The stations are listed in geographical order and given consecutive numbers. At the end of the volume an alphabetical listing is given, and for each entry a consecutive number is shown, to assist in finding the entry in the table.

- The list of places includes both subordinate and reference stations.

- The approximate latitude and longitude are given to assist in locating the station.

- The time difference in hours and minutes to be applied to the time at the reference station to find the time of the corresponding tide at the subordinate station.

- The height differences to be applied to the heights at the reference station to find the height of the corresponding tide at the subordinate station. The differences in heights are given for high and low water at spring tides and if available for high and low water at neap tides too. In case all four values are given the tables provide additional information about the applicable Moon phase and the delay of the appearance of the spring tide at the reference station. With this supplementary information the user can decide whether there is ***spring, or neap tide*** at the subordinate station and use the appropriate correction value. If the supplementary information points to a ***mean tide*** the arithmetical mean of the spring and neap values shall be used.

New Moon				**First Quarter**				**Full Moon**				**Last Quarter**			
	d	**h**	**m**		**d**	**h**	**m**		**d**	**h**	**m**		**d**	**h**	**m**
								Jan.	05	12	10				
Jan.	19	14	11	Jan.	27	05	11	Feb.	04	03	56	Jan.	12	19	55
Feb.	18	03	37	Feb.	26	02	50	Mar.	05	17	13	Feb.	11	04	07
Mar.	19	18	33	Mar.	27	22	27	Apr.	04	04	09	Mar.	12	11	35
Apr.	18	10	35	Apr.	26	14	42	May	03	13	03	Apr.	10	19	15
May	18	02	51	May	26	03	20	June	01	20	31	May	10	04	08
June	16	18	23	June	24	12	44	July	01	03	24	June	08	15	07
July	16	08	37	July	23	19	38	July	30	10	52	July	08	04	39
Aug.	14	21	31	Aug.	22	01	04	Aug.	28	20	10	Aug.	06	20	40
Sept.	13	09	23	Sept.	20	06	18	Sept.	27	08	17	Sept.	05	14	33
Oct.	12	20	31	Oct.	19	12	46	Oct.	26	23	35	Oct.	05	09	21
Nov.	11	07	09	Nov.	17	21	52	Nov.	25	17	31	Nov.	04	03	58
Dec.	10	17	33	Dec.	17	10	37	Dec.	25	12	49	Dec.	03	21	16

Figure 2520a Moon phases for the calendar year 2007 (time in UTC)

Spring / mid and neap tides are following each other as shown in Fig. 2520b below.

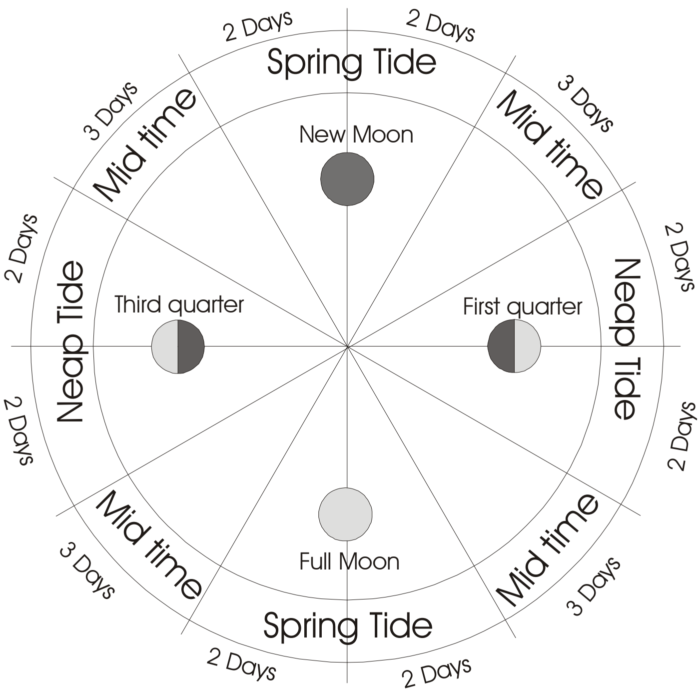


Figure 2520b Influence of the Moon phases on the tides

2530 Tide calculations

Applying the cosine square law the following equations can be used to solve tidal problems:

- Tide height against low water: (1) $\Delta H = Ts \bullet \cos^2(\frac{U}{Sd} \bullet 90)$
- Time difference to high water: (2) $U = \frac{Sd}{90} \bullet \arccos\sqrt{\frac{\Delta H}{Ts}}$
- Depth of water: (3) $Wt = Kt + Hgz + \Delta H$

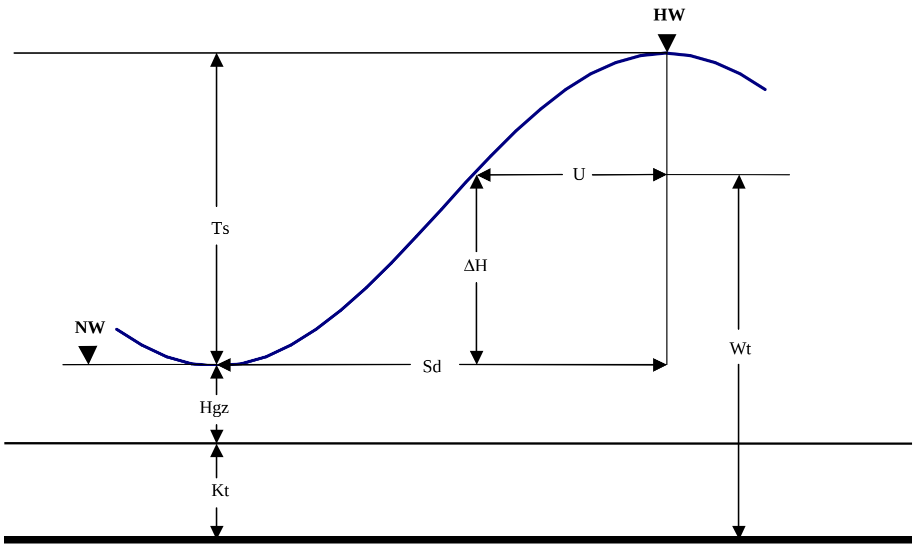


Figure 2530 Cosine square behaviour of tide rise and fall

The indices used above are:

- Kt = Charted depth
- Hgz = Difference of low water against Charted depth (it may be negative too)
- Ts = Tide Range (difference between high and low water)
- Sd = Time difference between high and low water

Example 1: *The captain of a vessel drawing 7 m wishes to pass over a temporary obstruction near station S subordinate to the reference station R, having a charted depth of 6,5 m, passage to be made during the morning of Day D. Required: The earliest and the latest time after 08 00 that the passge can be made, allowing a safety margin of 1 m.*

Answer: *For the day D the tidal tables for the reference station R provides the following information:*

LW -0,9 m at 04 59
HW +3,4 m at 11 20

The time and height differences against the reference station R given in the tidal tables for the subordinate station S are:

LW +0,2 m / +23 Minutes
HW -0,5 m / +24 Minutes

The tidal data for the subordinate station S are therefore as follows:

LW (-0,9 + 0,2)=-0,7 m at (04 59 + 00 23)=05 22
HW (3,4 - 0,5)=2,9 m at (11 20 + 00 24)=11 44

Tide range Ts=0,7 + 2,9=3,6 m
Tide duration Sd=11 44 – 05 22=6,3667 Hours
Formula (3) above provides the depth of water needed by the vessel:

$$Wt = Kt + Hgz + \Delta H$$

Wt = Draft of the vessel plus safety margin = 7+1=8 m

Kt = Charted depth of the obstruction = 6,5 m
Hgz = LW Height against the charted depth of the obstruction = -0,7 m
ΔH = Required height of the tide against LW at the time of passage.

DH = Wt – Kt – Hgz = 8 - 6,5 + 0,7 = 2,2 m

The time difference U against HW in order to reach the required ΔH can be calculated with the formula (2) above as follows:

$$U = \frac{Sd}{90} \bullet \arccos\sqrt{\frac{\Delta H}{Ts}} = \frac{6,3667}{90} \bullet \arccos\sqrt{\frac{2,2}{3,6}} = 2,7292 hroures$$

Passage is therefore possible 02 hours and 44 Minutes Prior and after the first HW of the Day D, i.e. between 09 00 and 13 28.

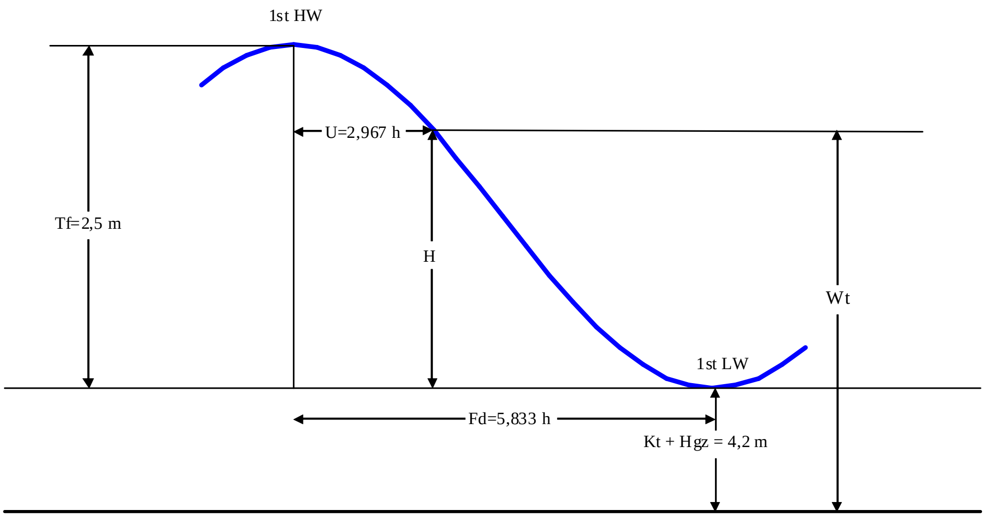
Example 2: *The captain of a vessel drawing 3,2 m wishes to anchor in front of Harwich harbour March the 14th 1977. Which depth should be measured at 10 35 UTC+1 in order to make sure that at the next LW there will be a residual safety depth under the vessels keel of 1,0 m?*

Answer: *From Fig. 2520a above the following information can be extracted: 12.03.1977 at 11 35 UTC the Moon is at its last quarter. This means that up to 11 35 UTC of March the 14th 1977 it is neap tide at the reference station of Harwich which is Immingham.*

From the tidal tables for Harwich it is evident that the time difference for HW against the reference station Immingham is + 06h 06´ and for LW is +05h 44´ and that the tidal height difference at neap tide for HW is –2,4 m and for LW is –1,5 m. Due to the fact the captain wishes to anchor at 10 35 UTC+1, i.e. prior to12 35 UTC+1 only the first HW and the first LW from Immingham are from interest.

	1st HW	*1st LW*
Immingham	*5,9 m at 01 31 UTC+1*	*2,5 m at 07 43 UTC+1*
Differences of the subordinate station	*-2,4 m / +06 06*	*-1,5 m / +05 44*
	1st HW	*1st LW*
Harwich	*3,5 m at 07 37 UTC+1*	*1,0 m at 13 27 UTC+1*

The water depth at LW should not be less than the vessels draft (3,2 m) plus the safety margin of 1,0 m, i.e. 4,2 m. The fall of the tide in Harwich is Tf = 3,5-1,0= 2,5 m, whilst its duration is 13h 27´- 07h 37´= 05h 50´ i.e. Fd = 5.833 h
The difference between HW and the time the vessel is anchoring is:
10h 35´ - 07h 37´ = 02h 58´ i.e. U = 2,967 h.



The depth to be measured at 09h 35´UTC+1 is therefore:
Wt =4,2+ΔH =4,2+Tf . cos²(90.U/Fd) = 4,2+2,5.cos²(90.2,967/5,833) = 5.4 m.

Example 3: *A vessel drawing 2,3 m wishes to enter Cranz in the morning of February the 18th 1973 and maintain a safety depth under its keel of 0,5 m. When is the latest time of arrival if the charted depth at Cranz is Kt = 1,9 m. When is the earliest time in the afternoon to enter Cranz, should the vessel arrive to late to enter in the morning?*

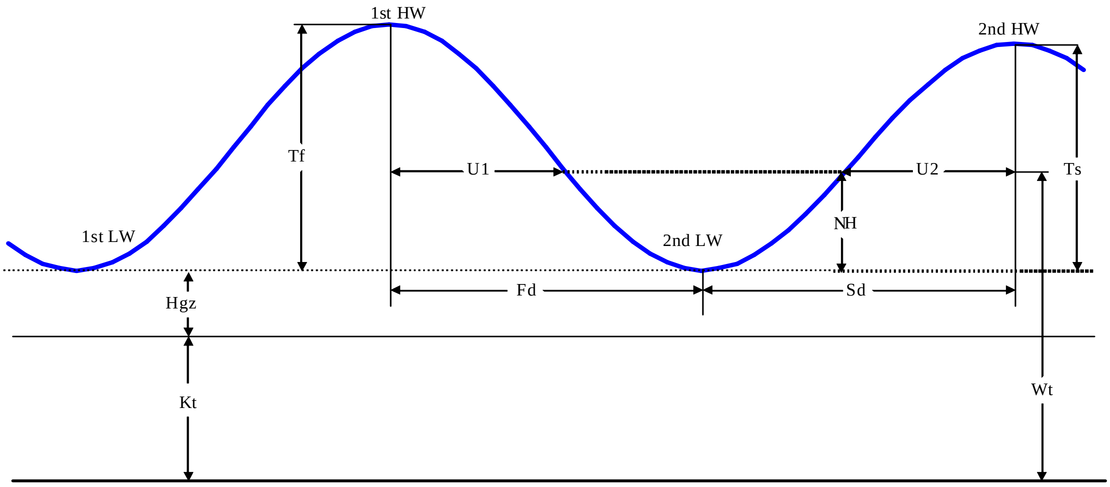
Answer: *From the Moon phases table applicable for the year 1973 the following information can be extracted:*
17.02.73 at 10 07 UTC is full Moon and therefore the start of the spring tide. The tidal tables for the year 1973 indicate that the spring delay for Hamburg which is the reference station for Cranz amounts to 3 days and 4 hours.

Full Moon	*17.02.73*	*10 07 UTC*
Spring delay in Hamburg	*3 days*	*4 hours*
Spring time at the reference station:	***20.02.73***	***at 15 07 UTC+1***

It is therefore evident that at the subordinate station February the 18th 1973 is mid tide period prior to 15 07 UTC+1, and spring tide period beyond 15 07 UTC+1.

From the tidal tables for the year 1973 the following information can be extracted for February the 18th:

	1^{st} *LW*	1^{st} *HW*	2^{nd} *LW*	2^{nd} *HW*
Hamburg	*00 48/0,0 m*	*05 42/2,7m*	*13 25/0,0 m*	*18 13/2,5 m*
Differences	*-00 32/0,05 m*	*-00 27/-0,1 m*	*-00 32/0,05 m*	*-00 27/-0,1 m*
Cranz	*00 16/0,05 m*	*05 15/2,6 m*	*12 53/0,05 m*	*17 46/2,4*



Tf = 2,6 - 0,05 = 2,55 m *Ts = 2,4 - 0,05 = 2,35 m*
Fd = 12 53 - 05 15 = 07 38 = 7,63h *Sd = 17 46 - 12 53 = 04 53 = 4,88 h*
Wt = Vessels draft + safety margin = 2,3 + 0,5 = 2,8 m
ΔH = Wt – Hgz – Kt = 2,8 – 0,05 – 1,9 = 0,85 m
*ΔH = Tf*cos²(U1*90/Fd) = Ts*cos²(U2*90/Sd)*

$$U1 = \frac{Fd}{90} * \arccos\sqrt{\frac{\Delta H}{Tf}} = 4{,}64h = 04h\ 38'$$

$$U2 = \frac{Sd}{90} * \arccos\sqrt{\frac{\Delta H}{Ts}} = 2{,}875h = 02h\ 53'$$

Arrival not later than: *1^{st} HW + U1 = 05 15 + 04 38 = 09 53 UTC + 1*
and not earlier than: *2^{nd} HW - U2 = 17 46 - 02 53 = 14 53 UTC + 1*

2540 Current sailing

The true course of a vessel is identical to its course over ground provided its behaviour is not influenced by wind or current. In presence of a current the vessel's course through the water **(KdW)**, which is its compass course corrected for deviation and variation, needs an additional current correction **(β)** to determine the vessel's course over ground **(COG)** and its speed over ground **(SOG)**. The value of said correction is depending upon the vessel's speed through the water **(FdW)**, its KdW, the speed of the current **(S)** and its direction **(δ)**.

The figure 2540 below exhibits a so called current triangle, illustrating a typical situation of a vessel's behaviour in presence of current.

The angle φ of the current triangle can be determined from the relationships α=180 - Kdw and α + δ + 180 - φ=180, respectively 180 – KdW + δ + 180 - φ=180.

$$\textbf{(1)} \qquad \varphi = 180 - (KdW - \delta)$$

The speed over ground of the vessel can be calculated by the cosines law equation exhibited in §5320 i.e. $SOG^2 = FdW^2 + S^2 - 2 * FdW * S * \cos\varphi$

$$\textbf{(2)} \qquad SOG = \sqrt{FdW^2 + S^2 - 2 * FdW * S * \cos\varphi}$$

The course over ground of the vessel is determined by $COG = KdW - \beta$ whilst β can be calculated by the sinus law equation exhibited in §5320 too, i.e. $\frac{SOG}{\sin\varphi} = \frac{S}{\sin\beta}$

$$\textbf{(3)} \qquad COG = KdW - \arcsin\frac{S * \sin\varphi}{SOG}$$

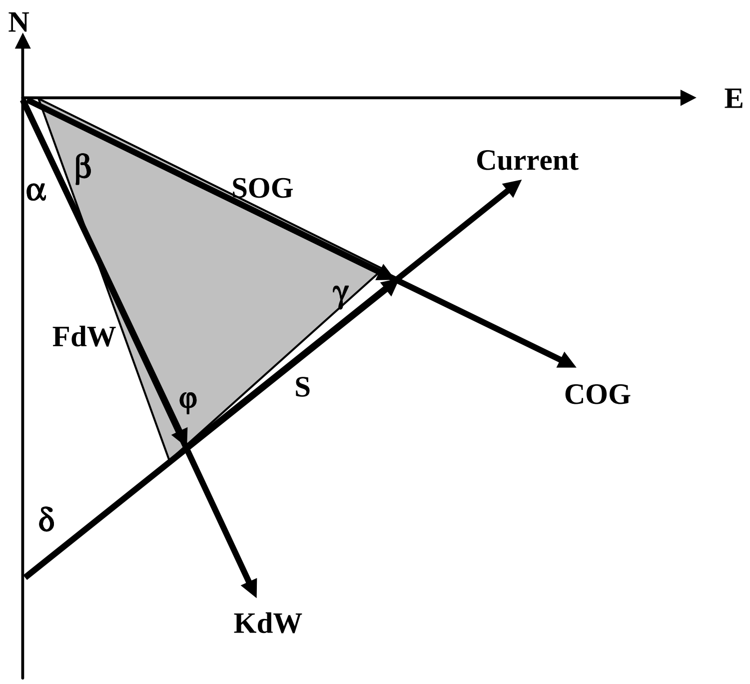


Figure 2540 Current triangle

Example: *The captain of a vessel experiencing a current with a drift of 2,1 Kn and setting towards 35°, wish to maintain a course over ground of 147°. The magnetic variation of the sailing area of the vessel is 3,9° E and the deviation of its magnetic compass at compass headings between 160° and 180° is nearly constant (-6,5°). Required: The compass course to be steered if the maximum speed of the vessel through the water is 6,5 Kn.*

Answer: *The following information can be extracted from the Figure 2540 above:*

$\alpha + \beta + COG = 180°$; $\alpha + \beta + \gamma + \delta = 180°$

$$\underline{\gamma = COG - \delta = 112°}$$

From the cosines law the vessel's speed over ground can be calculated as follows:

$$FdW^2 = SOG^2 + S^2 - 2 * SOG * S * \cos\gamma \text{ respectively}$$
$$SOG^2 + (-2 * S * \cos\gamma) * SOG + \left(S^2 - FdW^2\right) = 0$$

A solution of this second order equation is given in §5320 as follows:

$$SOG_{1,2} = \frac{2 * S * \cos\gamma \pm \sqrt{(-2 * S * \cos\gamma)^2 - 4 * (S^2 - FdW^2)}}{2}$$

SOG = 5,4 Kn

The current correction β can be calculated from the cosines law again as follows:

$$S^2 = SOG^2 + FdW^2 - 2 * SOG * FdW * \cos\beta$$

$$\beta = \arccos\frac{SOG^2 + FdW^2 - S^2}{2 * SOG * FdW}$$

$$\underline{\beta = 17{,}4°}$$

The compass course to be steered in order to maintain the required course over ground is therefore:

CH = COG + β – Magnetic Variation – Compass Deviation = 167°

PART 3

(Celestial navigation)

Chapter 1

(Navigational astronomy)

3110 Definitions

- **Astronomy** predicts the future positions and motions of celestial bodies and seeks to understand and explain their physical properties. Navigational astronomy, dealing principally with celestial coordinates, time, and the apparent motions of celestial bodies, is the branch of astronomy most important to the navigator.

- **The celestial sphere** is the inner surface of a vast, Earth centred sphere on which the celestial bodies are located. This model is useful since we are only interested in the relative positions and motions of celestial bodies on this imaginary surface. Understanding the concept of the celestial sphere is most important when discussing sight reduction in chapter 4 of part 3.

- **Celestial bodies are in constant motion**. There is no fixed position in space from which one can observe absolute motion. Since all motion is relative, the position of the observer must be noted when discussing planetary motion. From the Earth we see apparent motions of celestial bodies on the celestial sphere. In considering how planets follow their orbits around the Sun, we assume a hypothetical observer at some distant point in space. When discussing the rising or setting of a body on a local horizon, we must locate the observer at a particular point on the Earth because the setting Sun for one observer may be the rising Sun for another.

- Consider the celestial sphere as having an infinite radius because distances between celestial bodies are remarkably vast. Because of the size of **celestial distances**, it is inconvenient to measure them in common units such as the mile or kilometre. A commonly-used unit is the light-year, the distance light travels in one year. The nearest stars, Alpha Centauri and its neighbour Proxima, are 4,3 light-years away. Relatively few stars are less than 100 light-years away. The nearest galaxies, the Clouds of Magellan, are 150.000 to 200.000 light years away. The most distant galaxies observed by astronomers are several billion light years away.

- The Sun, the most conspicuous celestial object in the sky, is the central body of the solar system. Associated with it are at least nine principal **planets (**including Pluto) and thousands of asteroids, comets, and meteors. Some planets like Earth have satellites.

- We must distinguish between two principal **motions of celestial bodies** in the Solar System. **Rotation** is a spinning motion about an axis within the body, whereas **revolution** is the motion of a body in its orbit around another body.

- The hierarchies of motions in the universe are caused by the **force of gravity**. As a result of gravity, bodies attract each other in proportion to their masses and to the inverse square of the distances between them. This force causes the planets to go around the Sun in **nearly circular, elliptical orbits**. In each planet's orbit, the point nearest the Sun is called the **perihelion**. The point farthest from the Sun is called the **aphelion**. The line joining perihelion and aphelion is called the **line of apsides**. In the orbit of the Moon, the point nearest the Earth is called the **perigee**, and that point farthest from the Earth is called the **apogee**. Figure 3110 shows the orbit of the Earth (with exaggerated eccentricity), and the orbit of the Moon around the Earth

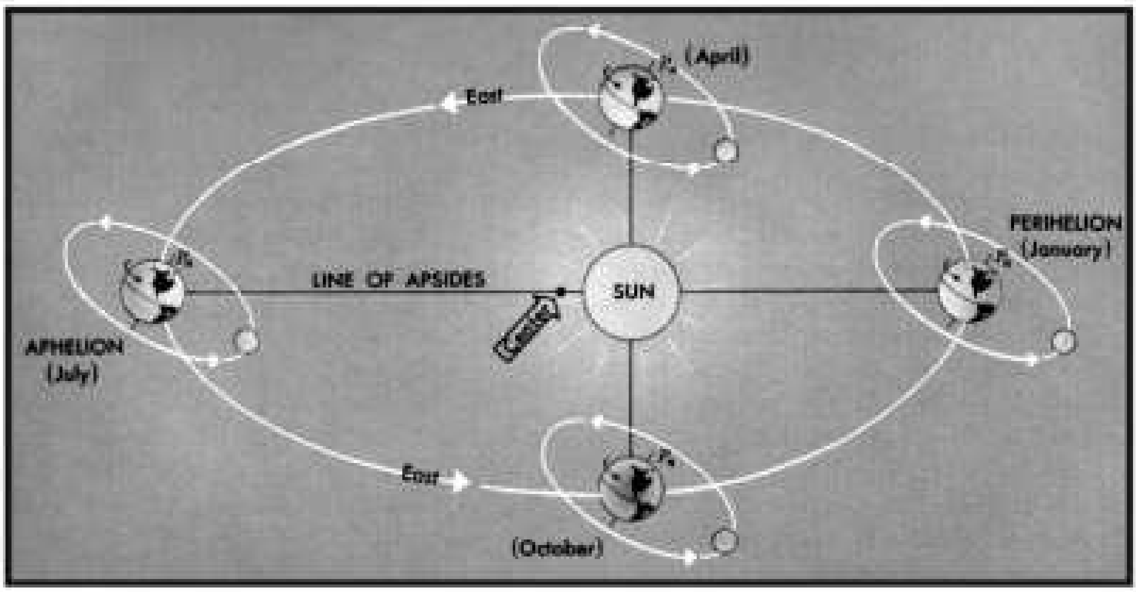


Figure 3110 The orbit of the Earth

3120 The Earth

In common with other planets, the Earth **rotates** on its axis and **revolves** in its orbit around the Sun. These motions are the principal source of the daily apparent motions of other celestial bodies. The Earth's rotation also causes a deflection of water and air currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

For most navigational purposes, the Earth can be considered a sphere. However, like the other planets, the Earth is approximately an **oblate spheroid**, or **ellipsoid of revolution**, flattened at the poles and bulged at the equator (Ref. Figure 3120). Therefore, the polar diameter is less than the equatorial diameter, and the meridians are slightly elliptical, rather than circular.

The dimensions of the Earth are recomputed from time to time, as additional and more precise measurements become available. Since the Earth is not exactly an ellipsoid, results differ slightly when equally precise and extensive measurements are made on different parts of the surface.

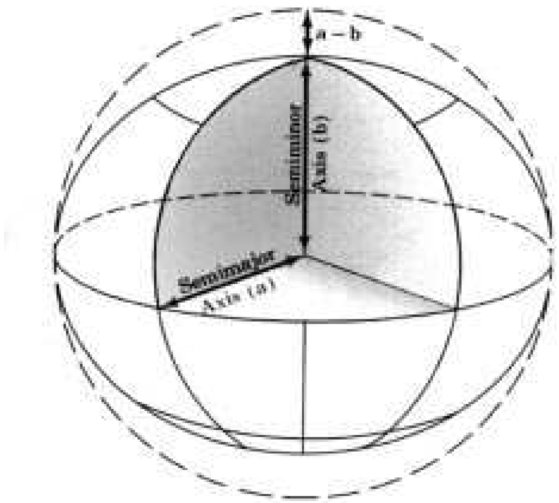


Figure 3120 Oblate spheroid or ellipsoid of revolution

3130 The Ecliptic

The **ecliptic** is the path the Sun appears to take among the stars due to the annual revolution of the Earth in its orbit. It is considered a great circle of the celestial sphere, inclined at an angle of about 23°26' to the celestial equator, but undergoing a continuous slight change. This angle is called the **obliquity of the ecliptic**. This inclination is due to the fact that the axis of rotation of the Earth is not perpendicular to its orbit. It is this inclination which causes the Sun to appear to move north and south during the year, giving the Earth its seasons and changing lengths of periods of daylight.

- The Earth is at perihelion early in January and at aphelion 6 months later (Ref. Figure 3130). On or about June 21, about 10 or 11 days before reaching aphelion, the northern part of the Earth's axis is tilted toward the Sun. The north polar regions are having continuous Sunlight; the Northern Hemisphere is having its summer with long, warm days and short nights; the Southern Hemisphere is having winter with short days and long, cold nights; and the south polar region is in continuous darkness. This is the **summer solstice**.

- Three months later, about September 23, the Earth has moved a quarter of the way around the Sun, but its axis of rotation still points in about the same direction in space. The Sun shines equally on both hemispheres, and days and nights are the same length over the entire world. The Sun is setting at the North Pole and rising at the South Pole. The Northern Hemisphere is having its autumn, and the Southern Hemisphere its spring. This is the **autumnal equinox**.

- In another three months, on or about December 22, the Southern Hemisphere is tilted toward the Sun and conditions are the reverse of those six months earlier; the Northern Hemisphere is having its winter, and the Southern Hemisphere its summer. This is the **winter solstice**.

- Three months later, when both hemispheres again receive equal amounts of Sunshine, the Northern Hemisphere is having spring and the Southern Hemisphere autumn, the reverse of conditions six months before. This is the **vernal equinox**.

- The word **“equinox,”** meaning “equal nights,” is applied because it occurs at the time when days and nights are of approximately equal length all over the Earth. The word **“solstice,”** meaning “Sun stands still,” is applied because the Sun stops its apparent northward or southward motion and momentarily “stands still” before it starts in the opposite direction. This action, somewhat analogous to the “stand” of the tide, refers to the motion in a north-south direction only, and not to the daily apparent revolution around the Earth. Note that it does not occur when the Earth is at perihelion or aphelion.

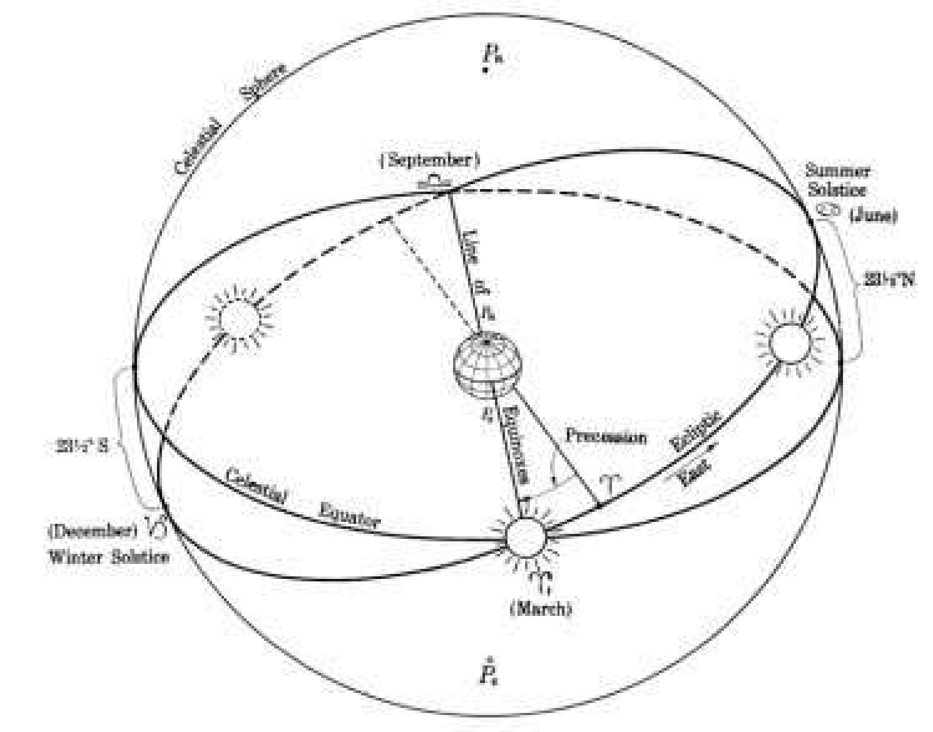


Figure 3130 Apparent motion of the Sun in the ecliptic

- At the time of the vernal equinox, the Sun is directly over the equator, crossing from the Southern Hemisphere to the Northern Hemisphere. It rises due east and sets due west, remaining above the horizon for approximately 12 hours. It is not exactly 12 hours because of refraction, semi diameter, and the height of the eye of the observer. These cause it to be above the horizon a little longer than below the horizon. Following the vernal equinox, the northerly declination increases, and the Sun climbs higher in the sky each day (at the latitudes of the northern hemisphere), until the summer solstice, when a declination of about 23°26' north of the celestial equator is reached. The Sun then gradually retreats southward until it is again over the equator at the autumnal equinox, at about 23°26' south of the celestial equator at the winter solstice, and back over the celestial equator again at the next vernal equinox.

- Everywhere between the parallels of about 23°26'N and about 23°26'S the Sun is directly overhead at some time during the year. Except at the extremes, this occurs twice: once as the Sun appears to move northward and the second time as it moves southward. This is the **Torrid Zone**. The northern limit is the **Tropic of Cancer**, and the southern limit’s the **Tropic of Capricorn**. The parallels about 23°26' from the poles, marking the approximate limits of the circumpolar Sun, are called **polar circles**, the one in the Northern Hemisphere being the **Arctic Circle** and the one in the Southern Hemisphere the **Antarctic Circle**. The areas inside the polar circles are the north and south **frigid zones**. The regions between the frigid zones and the torrid zones are the north and south **temperate zones**.

- The expression “vernal equinox” and associated expressions are applied both to the *times* and *points of occurrence* of the various phenomena. Navigationally, the vernal equinox is of interest to navigators because it is the origin for measuring **sidereal hour angle**. The expressions March equinox, June solstice, September equinox, and December solstice are occasionally applied as appropriate, because the more common names are associated with the seasons in the Northern Hemisphere and are six months out of step for the Southern Hemisphere.

3140 Time

Traditionally, astronomy has furnished the basis for measurement of time, a subject of primary importance to the navigator. The **year** is associated with the revolution of the Earth in its orbit. The **day** is one rotation of the Earth about its axis.

The duration of one rotation of the Earth depends upon the external reference point used. One rotation relative to the Sun is called a **solar day**. However, rotation relative to the apparent Sun (the actual Sun that appears in the sky) does not provide time of uniform rate because of variations in the rate of revolution and rotation of the Earth. The error due to lack of uniform rate of revolution is removed by using a fictitious **mean Sun**. Thus, mean solar time is nearly equal to the average apparent solar time. Because the accumulated difference between these times, called the **equation of time**, is continually changing, the period of daylight is shifting slightly, in addition to its increase or decrease in length due to changing declination. Apparent and mean Suns seldom cross the celestial meridian at the same time.

Universal Time is a particular case of the measure known in general as mean solar time. **Universal Time is the mean solar time on the Greenwich meridian**, reckoned in days of 24 mean solar hours beginning with 0 hours at midnight. **Universal Time is the standard in the application of astronomy to navigation**.

If the vernal equinox is used as the reference, a **sidereal day** is obtained, and from it, **sidereal time**. This indicates the approximate positions of the stars, and for this reason it is the basis of star charts and star finders. Universal Time and sidereal time are rigorously related by a formula so that if one is known the other can be found.

Time is also classified according to the terrestrial meridian used as a reference. **Local time** results if one’s own meridian is used, **zone time** if a nearby reference meridian is used over a spread of longitudes, and **Greenwich** or **Universal Time** if the Greenwich meridian is used.

The period from one vernal equinox to the next (the cycle of the seasons) is known as the **tropical year**. It is approximately 365 days, 5 hours, 48 minutes, 45 seconds, though the length has been slowly changing for many centuries. Our calendar, the Gregorian calendar, approximates the tropical year with a combination of **common years of 365 days and leap years of 366 days**. A leap year is any year divisible by four, unless it is a century year, which must be divisible by 400 to be a leap year. Thus, 1700, 1800, and 1900 were not leap years, but 2000 was one.

3150 Eclipses

If the orbit of the Moon coincided with the plane of the ecliptic, the Moon would pass in front of the Sun at every new Moon, causing a solar eclipse. At full Moon, the Moon would pass through the Earth's shadow, causing a lunar eclipse.

Because of the Moon's orbit is inclined 5° with respect to the ecliptic, the Moon usually passes above or below the Sun at new Moon and above or below the Earth's shadow at full Moon. However, there are two points at which the plane of the Moon's orbit intersects the ecliptic. These are the **nodes** of the Moon's orbit. If the Moon passes one of these points at the same time as the Sun, a **solar eclipse** takes place (Ref. Figure 3150).

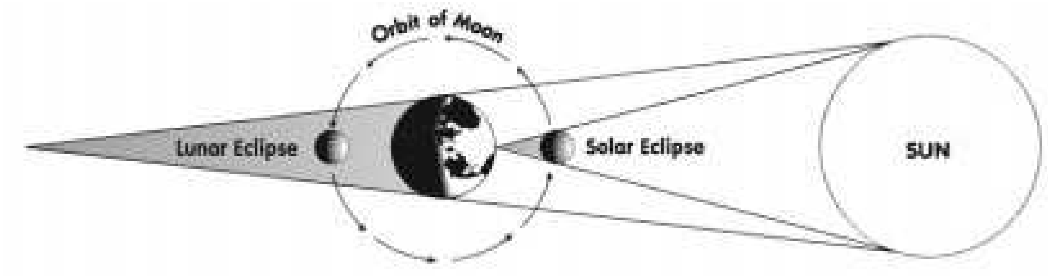


Figure 3150 Eclipses of the Sun and Moon

The Sun and Moon are of nearly the same apparent size to an observer on the Earth. If the Moon is **at perigee**, the Moon's apparent diameter is larger than that of the Sun, and its shadow reaches the Earth as a nearly round dot only a few miles in diameter. The dot moves rapidly across the Earth, from west to east, as the Moon continues in its orbit. Within the dot, the Sun is completely hidden from view, and a **total eclipse** of the Sun occurs.

For a considerable distance around the shadow, a part of the surface of the Sun is obscured and a **partial eclipse** occurs. In the line of travel of the shadow a partial eclipse occurs as the round disk of the Moon appears to move slowly across the surface of the Sun, hiding an ever-increasing part of it, until the total eclipse occurs.

The duration of a total eclipse depends upon how nearly the Moon crosses the centre of the Sun, the location of the shadow on the Earth, the relative orbital speeds of the Moon and Earth, and (principally) the relative apparent diameters of the Sun and Moon. The maximum length that can occur is a **little more than seven minutes**.

If the Moon is **near apogee**, its apparent diameter is less than that of the Sun, and its shadow does not quite reach the Earth. Over a small area of the Earth directly in line with the Moon and Sun, the Moon appears as a black disk almost covering the surface of the Sun, but with a thin ring of the Sun around its edge. This **annular eclipse** occurs a little more often than a total eclipse.

An eclipse of the Moon (or **lunar eclipse**) occurs when the Moon passes through the shadow of the Earth (Ref. Figure 3150). Since the diameter of the Earth is about 3 ½ times that of the Moon, the Earth's shadow at the distance of the Moon is much larger than that of the Moon. A total eclipse of the Moon can last nearly **1 3/4 hours**, and some part of the Moon may be in the Earth's shadow for almost 4 hours.

3160 The celestial sphere

The **celestial sphere** is an imaginary sphere of infinite radius with the Earth at its centre (Ref. Figure 3160a). The north and south celestial poles of this sphere are located by extension of the Earth's axis. The **celestial equator** (sometimes called **equinoctial**) is formed by projecting the plane of the Earth's equator to the celestial sphere. A **celestial meridian** is formed by the intersection of the plane of a terrestrial meridian and the celestial sphere. It is the arc of a great circle through the poles of the celestial sphere.

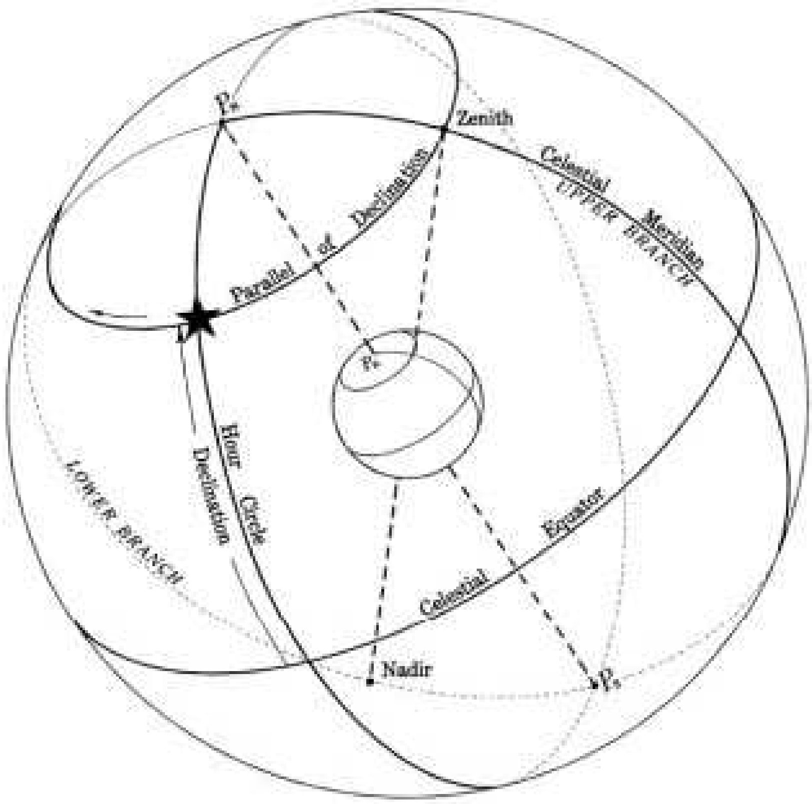


Figure 3160a The celestial sphere

The point on the celestial sphere vertically overhead of an observer is the **zenith**, and the point on the opposite side of the sphere vertically below him is the **nadir**. The zenith and nadir are the extremities of a diameter of the celestial sphere through the observer and the common centre of the Earth and the celestial sphere. The arc of a celestial meridian between the poles is called the **upper branch** if it contains the zenith and the **lower branch** if it contains the nadir. The upper branch is frequently used in navigation, and references to a celestial meridian are understood to mean only its upper branch, unless otherwise stated. Celestial meridians take the names of their terrestrial counterparts, such as 65° west.

An **hour circle** is a great circle through the celestial poles and a point or body on the celestial sphere. It is similar to a celestial meridian, **but moves with the celestial sphere** as it rotates about the Earth, **while a celestial meridian remains fixed** with respect to the Earth.

The location of a body on its hour circle is defined by the body's angular distance from the celestial equator. This distance, called **declination**, is measured north or south of the celestial equator in degrees, from 0° through 90°, similar to the latitude on the Earth.

A circle parallel to the celestial equator is called a **parallel of declination**, since it connects all points of equal declination. It is similar to a parallel of latitude on the Earth.

A point on the celestial sphere may be identified at the intersection of its parallel of declination and its hour circle. The parallel of declination is identified by the declination.

Two basic methods of locating the hour circle are in use. First, the angular distance west of a reference hour circle through a point on the celestial sphere, named the vernal equinox or first point of Aries, is called **sidereal hour angle (SHA)** (Figure 3160b). This angle, measured eastward from the vernal equinox, is called **right ascension** and is usually expressed in time units.

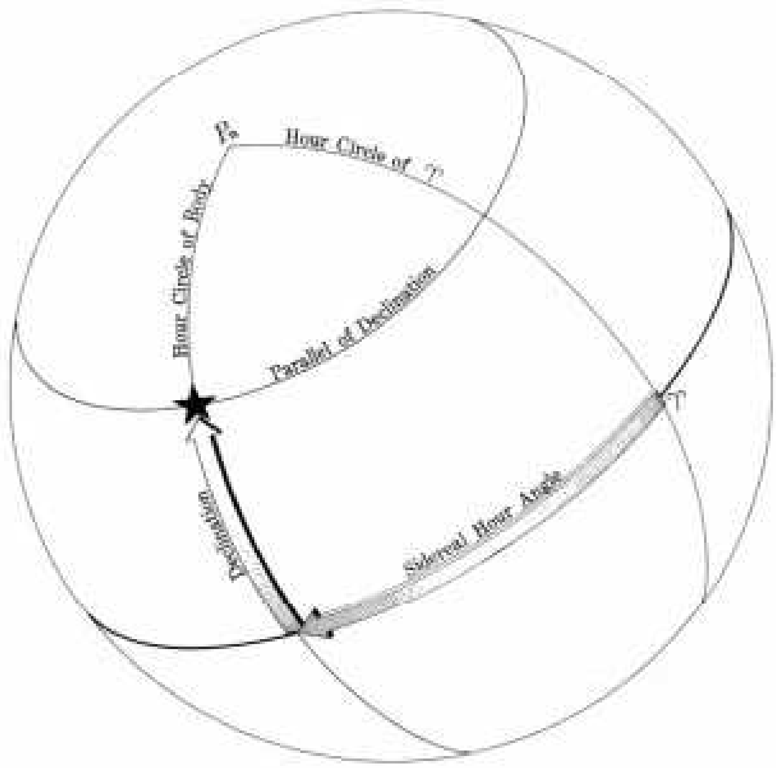


Figure 3160b Point on the celestial sphere located by its declination and sidereal hour angle

The second method of locating the hour circle is to indicate its angular distance west of a celestial meridian (Figure 3160c). If the Greenwich celestial meridian is used as the reference, the angular distance is called **Greenwich hour angle (GHA)**, and if the meridian of the observer, it is called **local hour angle (LHA)**. It is sometimes more convenient to measure the hour angle either eastward or westward, as longitude is measured on the Earth, in which case it is called **meridian angle** (designated "t").

A point on the celestial sphere may also be located using altitude and azimuth coordinates based upon the horizon as the primary great circle instead of the celestial equator.

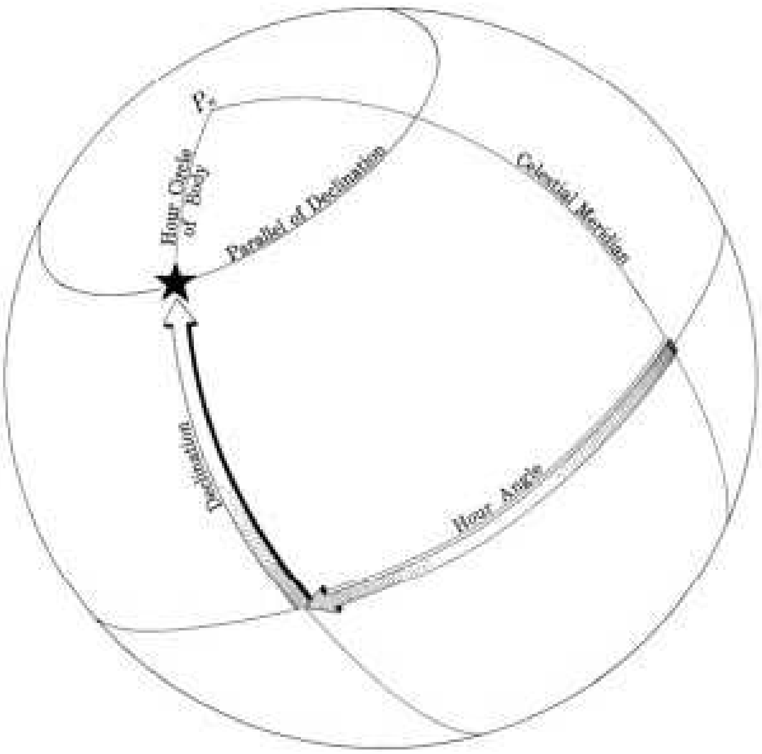


Figure 3160c Point on the celestial sphere located by its declination and hour angle

3170 Coordinate systems

In practical celestial navigation the navigator is primarily concerned with two systems of coordinates which are, the celestial equator system of coordinates and that of the horizon system.

3171 Celestial equator system of coordinates

On the celestial sphere latitude becomes declination, while longitude becomes sidereal hour angle, measured from the vernal equinox.

Declination is the angular distance north or south of the celestial equator (Ref. Figure 3171a). It is measured along an hour circle, from 0° at the celestial equator through 90° at the celestial poles. It is labelled N or S to indicate the direction of measurement. All points having the same declination lie along a parallel of declination.

Polar distance (p) is the angular distance from a celestial pole, or the arc of an hour circle between the celestial pole and a point on the celestial sphere. It is measured along an hour circle and may vary from 0° to 180°, since either pole may be used as the origin of measurement. It is usually considered the **complement of declination**, though it may be either 90° – d or 90° + d, depending upon the pole used.

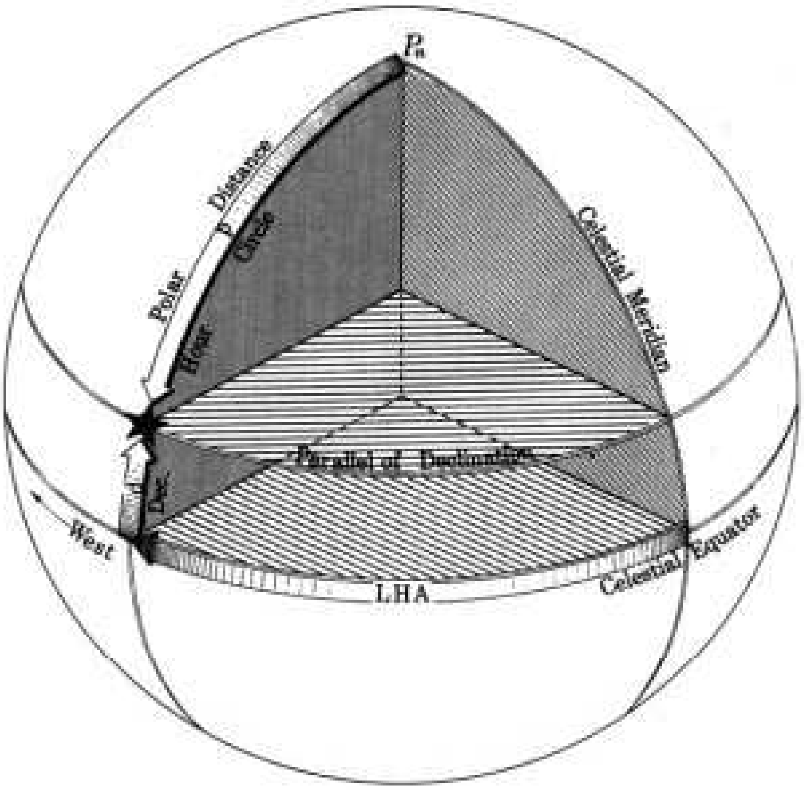


Figure 3171a The celestial equator system of coordinates

Local hour angle (LHA) is the angular distance west of the local celestial meridian, or the arc of the celestial equator between the upper branch of the local celestial meridian and the hour circle through a point on the celestial sphere, measured westward from the local celestial meridian, through 360°. It is also the similar arc of the parallel of declination and the angle at the celestial pole, similarly measured. If the Greenwich (0°) meridian is used as the reference, instead of the local meridian, the expression **Greenwich hour angle (GHA)** is applied. It is sometimes convenient to measure the arc or angle in either an easterly or westerly direction from the local meridian, through 180°, when it is called **meridian angle (t)** and labelled E or W to indicate the direction of measurement. All bodies or other points having the same hour angle lie along the same hour circle.

Because of the apparent daily rotation of the celestial sphere, hour angle continually increases, but meridian angle increases from 0° at the celestial meridian to 180°W, which is also 180°E, and then decreases to 0° again. **The rate of change for the mean Sun is 15° per hour**. The rate of all other bodies except the Moon is within 3' of this value. The average rate of the Moon is about 15.5°.

As the celestial sphere rotates, each body crosses each branch of the celestial meridian approximately once a day. This crossing is called **meridian transit** (sometimes called **culmination**). It may be called **upper transit** to indicate crossing of the upper branch of the celestial meridian, and **lower transit** to indicate crossing of the lower branch (Ref. §3340).

The **time diagram** shown in Figure 3171b illustrates the relationship between the various hour angles and meridian angle of the Sun (red lines) and the Moon (black lines).

The circle is the celestial equator as seen from above the South Pole, with the upper branch of the observer’s meridian (M) at the top. The radius at G is the Greenwich meridian; The Sun’s hour circle is to the east of the observer’s meridian; the Moon’s hour circle is to the west of the observer’s meridian Note that when LHA is less than 180°, it is numerically the same and is labelled W, but that when LHA is greater than 180°, t = 360° – LHA and is labelled E. In Figure 3171b arc GM is the longitude, which in this case is west.

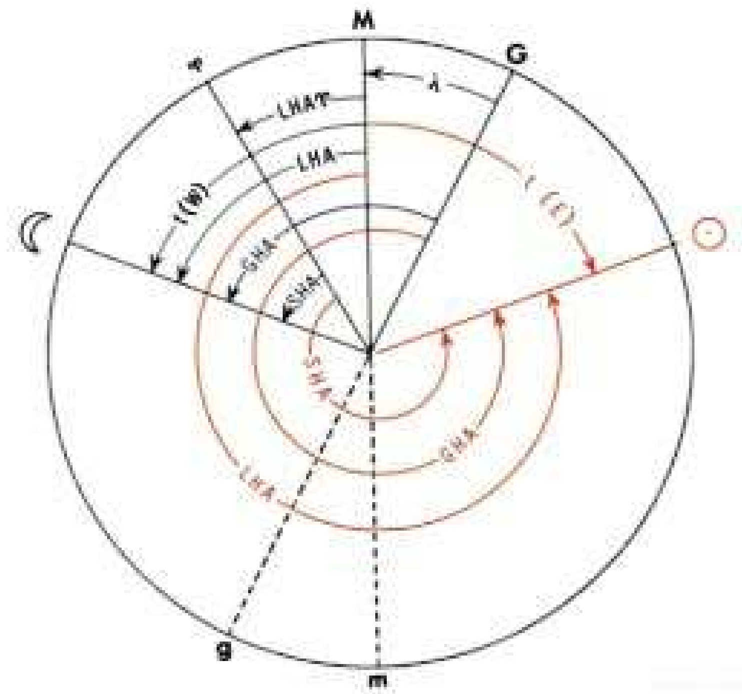


Figure 3171b Time diagram

Example: *An observer is at longitude 77° E. The Sun is 60° east of the local meridian, and the GHA of the Aries is 37°. Required: 1) GHA of the Sun. 2) LHA of the Sun. 3) SHA of the Sun. 4) Approximate time at the local meridian.*

Answer:
1) GHA=360 - longitude of the observer - t of the Sun=360 – 77 - 60=223°
2) LHA=GHA+ longitude of the observer=223 + 77=300°
3) SHA=GHA of the Sun-GHA of the Aries=223 - 37=186°
4) The Sun is 60°/15°=4 hours behind the meridian. The local time is therefore 08 00

3172 Horizon system of coordinates

As shown in Figure 3172, altitude is the angular distance above the horizon. It is measured along a vertical circle, from 0° at the horizon through 90° at the zenith. Altitude measured from the visible horizon may exceed 90° because of the dip of the horizon. Angular distance below the horizon, called negative altitude, is provided for by including certain negative altitudes in some tables for use in celestial navigation. All points having the same altitude lie along a parallel of altitude.

Zenith distance (z) is the angular distance from the zenith, or the arc of a vertical circle between the zenith and a point on the celestial sphere. It is measured along a vertical circle from 0° through 180°. It is usually considered the complement of altitude. For a body above the celestial horizon it is equal to 90° – h and for a body below the celestial horizon it is equal to 90° + h.

The horizontal direction of a point on the celestial sphere, or the bearing of the geographical position, is called **azimuth** or **azimuth angle** depending upon the method of measurement. In both methods it is an arc of the horizon (or parallel of altitude), or an angle at the zenith. It is **azimuth** (Zn) if measured clockwise through 360°, starting at the north point on the horizon, and **azimuth angle** (Z) if measured either clockwise or counter clockwise through 180°, starting at the north point of the horizon in north latitude and the south point of the horizon in south latitude.

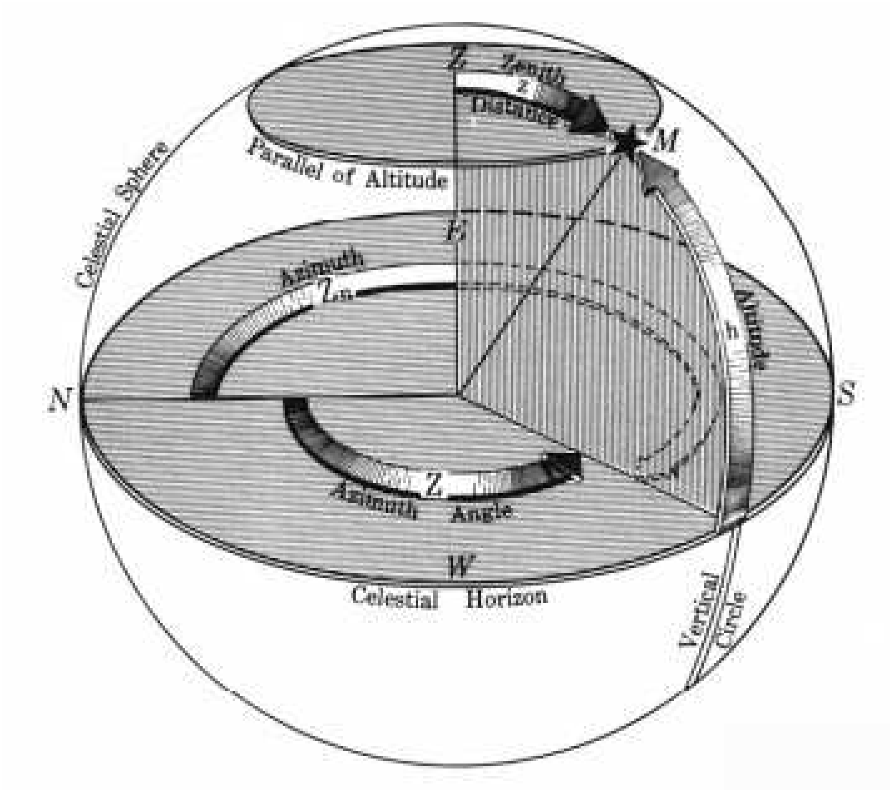


Figure 3172 The horizon system of coordinates

3180 Identification of stars

For stars identification 4 figures have been laid down in appendix C, which can be used as a guide to identify stars in the vicinity of Pegasus, of Orion, of Ursa Major and the vicinity of Cygnus.

PART 3

(Celestial navigation)

Chapter 2

(Instruments for celestial navigation)

3210 Marine sextant description and use

The marine sextant measures the angle between two points by bringing the direct image from one point and a double-reflected image from the other into coincidence. Its principal use is to measure the altitudes of celestial bodies above the visible sea horizon. It may also be used to measure vertical angles to find the range from an object of known height. Sometimes it is turned on its side and used for measuring the angular distance between two terrestrial objects.

A marine sextant can measure angles up to approximately 120°. Originally, the term “sextant” was applied to the navigator’s double-reflecting, altitude-measuring instrument only if its arc was 60° in length, or 1/6 of a circle, permitting measurement of angles from 0° to 120°. In modern usage the term is applied to all modern navigational altitude-measuring instruments regardless of angular range or principles of operation.

3211 Non adjustable sextant errors

The non-adjustable sextant errors are prismatic error, graduation error, and centering error. The higher the quality of the instrument, the less these error will be.

- **Prismatic error** occurs when the faces of the shade glasses and mirrors are not parallel.
- **Graduation errors** occur in the arc, micrometer drum, and vernier of a sextant which is improperly cut or incorrectly calibrated.
- **Cantering error** results if the index arm does not pivot at the exact centre of the arc’s curvature.

The manufacturer normally determines the magnitude of all three non-adjustable errors and reports them to the user as **instrument error**. The navigator should apply the correction for this error to each sextant reading.

3212 Adjustable sextant errors

The navigator should measure and remove the following adjustable sextant errors in the order listed:

- **Perpendicularity Error:** Adjust first for Perpendicularity of the index mirror to the frame of the sextant. To test for Perpendicularity, place the index arm at about 35° on the arc and hold the sextant on its side with the index mirror up and toward the eye. Observe the direct and reflected views of the sextant arc, as illustrated in Figure 3212a. If the two views are not joined in a straight line, the index mirror is not perpendicular. If the reflected image is above the direct view, the mirror is inclined forward. If the reflected image is below the direct view, the mirror is inclined backward. Make the adjustment using two screws behind the index mirror.

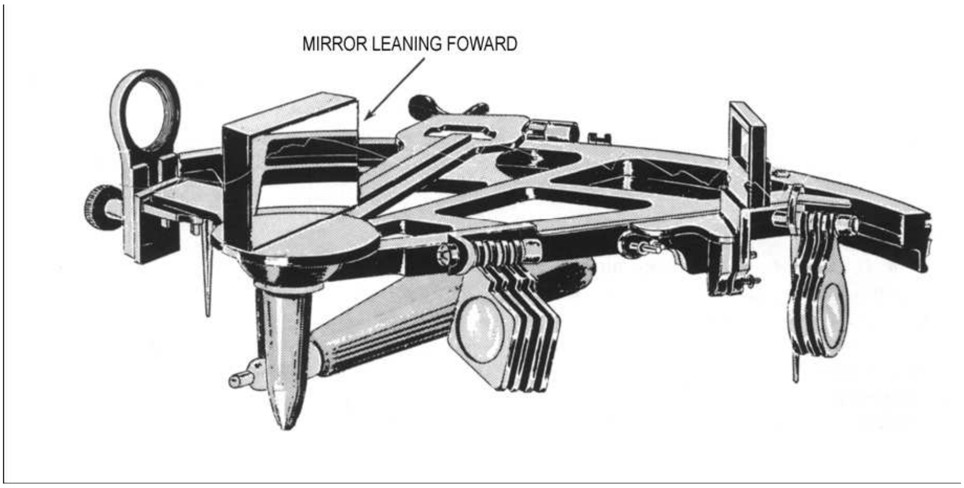


Figure 3212a Testing the Perpendicularity of the index mirror.

- **Side Error:** An error resulting from the horizon glass not being perpendicular is called side error. To test for side error, set the index arm at zero and direct the line of sight at a star. Then rotate the tangent screw back and forth so that the reflected image passes alternately above and below the direct view. If, in changing from one position to the other, the reflected image passes directly over the non reflected image, no side error exists. If it passes to one side, side error exists.

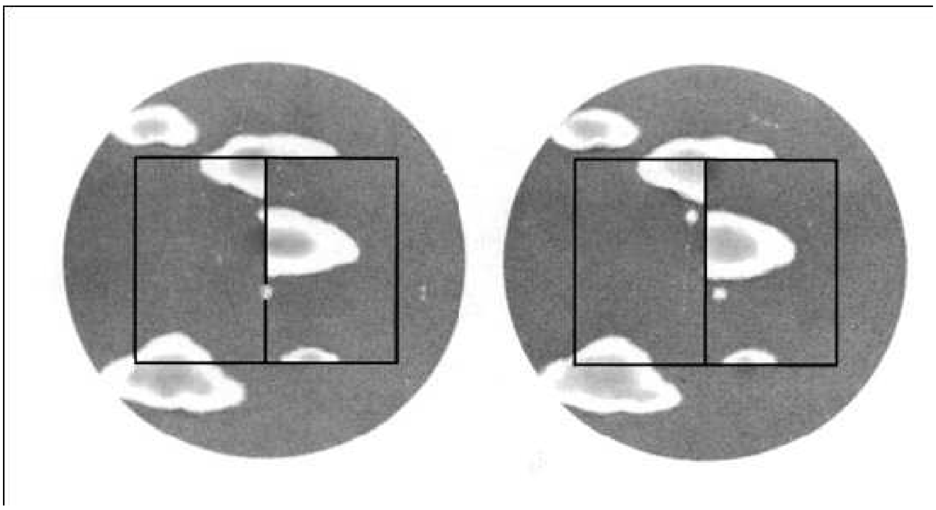


Figure 3212b Testing the Perpendicularity of the horizon glass.
On the left, a side error does not exist. At the right, a side error does exist.

Figure 3212b illustrates observations without side error (left) and with side error (right). Whether the sextant reads zero when the true and reflected images are in coincidence is immaterial for this test.

An alternative method is to observe a vertical line, such as one edge of the mast of another vessel (or the sextant can be held on its side and the horizon used). If the direct and reflected portions do not form a continuous line, the horizon glass is not perpendicular to the frame of the sextant.

A third method involves holding the sextant vertically, as in observing the altitude of a celestial body. Bring the reflected image of the horizon into coincidence with the direct view until it appears as a continuous line across the horizon glass. Then tilt the sextant right or left. If the horizon still appears continuous, the horizon glass is perpendicular to the frame, but if the reflected portion appears above or below the part seen directly, the glass is not perpendicular.

Make the appropriate adjustment using two screws behind the horizon glass.

- **Collimation Error:** If the line of sight through the telescope is not parallel to the plane of the instrument, a collimation error will result. Altitudes measured will be greater than their actual values. To check for parallelism of the telescope, insert it in its collar and observe two stars 90° or more apart. Bring the reflected image of one into coincidence with the direct view of the other near either the right or left edge of the field of view (the upper or lower edge if the sextant is horizontal). Then tilt the sextant so that the stars appear near the opposite edge. If they remain in coincidence, the telescope is parallel to the frame; if they separate, it is not. Adjust the collar screws to correct for non-parallelism.

Index Error: Index error is the error remaining after the navigator has removed Perpendicularity error, side error and collimation error. The index mirror and horizon glass not being parallel when the index arm is set exactly at zero is the major cause of index error. To test for parallelism of the mirrors, set the instrument at zero and direct the line of sight at the horizon. Adjust the sextant reading as necessary to cause both images of the horizon to come into line. The sextant's reading when the horizon comes into line is the index error. If the index error reading is to the left of the zero mark of the sextant limp, the values of all altitudes to be measured will be to high, and the sextant index error should therefore be treated as a negative quantity. If the index error reading is to the right of the zero mark of the sextant limp, the values of all altitudes to be measured will be to small, and the sextant index error should therefore be treated as a positive quantity.

An other simple method to determine the sextant index error is to observe the double reflected upper limp of the Sun when it touches the lower limp of the direct sighted Sun (negative reading) and subsequently the double reflected lower limp of the Sun when it touches the upper limp of the direct sighted Sun (positive reading). Half of the arithmetic sum of both readings is the sextant index error.

Example: *The sextant reading if the double reflected upper limp of the Sun touches the lower limp of the direct sighted Sun is –30´. The sextant reading if the double reflected lower limp of the Sun touches the upper limp of the direct sighted Sun is 35´. Sextant index error required.*

Answer:	*First reading*	*- 30´*
	Second reading	*+ 35´*
	Arithmetic Sum	***+ 5´***
	Index error	***+ 2,5´***

The method described above contains as an additional information a statement concerning the quality of the measurement, as the quarter of the absolute value of the sum of both readings is nothing else than the semi diameter of the Sun (65/4=16,25´).

3220 Sextant altitude corrections

The uncorrected reading of a sextant is called **Sextant altitude (hs).** Following proper adjustment of the sextant as explained above certain sources of error are eliminated. There remains, however, a number of sources of error over which the navigator has little or no control. For each of these he applies a correction. When all of these **sextant altitude corrections** have been applied, the value obtained is **the altitude of the centre of the celestial body** above the celestial horizon, **for an observer at the centre of the Earth**. This value called **observed altitude (ho)** is compared with the **computed altitude (hc)** to find the **altitude intercept (a)** used in establishing a line of position (Ref. Figure 3411).

3221 Instrument correction

Instrument (I) correction is the combined correction of all non adjustable errors of the sextant, as explained in §3211 above.

3222 Index correction

The **index correction (IC)** primarily caused by lack of parallelism of the horizon glass and the index mirror, is explained in §3212 above. As long as the adjustment remains undisturbed, IC remains constant and is applicable to all angles measured by the instrument.

3223 Dip

Dip of the horizon is the angle **(D)** by which the visible horizon (CA) differs from the horizontal at the eye of the observer (HA).

If the eye of the observer were at the surface of the Earth, the visible horizon (CA) would coincide with the horizontal (HA) and there would be no dip. This is never the situation aboard a vessel, however, and at any height above the surface of the Earth the visible horizon is normally below the horizontal, and an altitude measured from the visible horizon is too great and must be corrected.

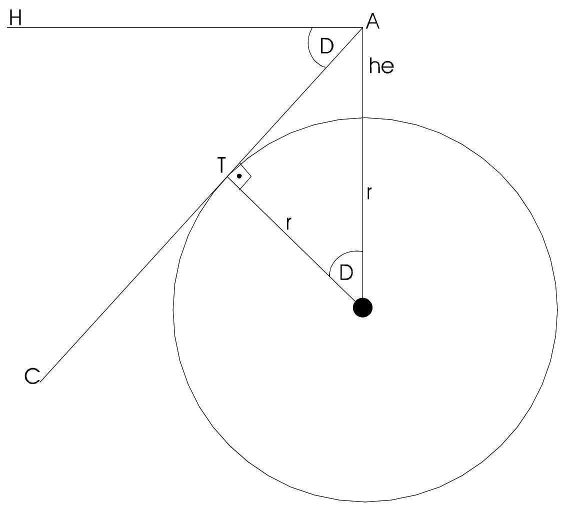


Figure 3223   Dip (D)

For a height of eye **(he) in meters**, this negative correction for dip **(D)** expressed in **minutes of arc** can be calculated as follows:

$$D = 1{,}779 * \sqrt{he}$$

It should be noted that said correction does not consider the influence of refraction, which especially in Polar Regions can be drastic.

3224 Refraction

Light or other radiant energy, is assumed to travel in a strait line at uniform speed, if the medium in which it is travelling has uniform properties. But if light enters a medium of different properties, particularly if the density is different, the speed of light changes somewhat. If the light enters a more dense medium at an oblige angle, the change of speed occurs progressively along the wave front as the different parts enter the more dense medium. This results in a change in the direction of travel. This change in direction of motion is called **refraction (R)**.

If the light enters a more dense medium at an angle perpendicular to the surface separating the two media– vertically downwards-, all parts of each wave front enter the new medium at the same time, and so all parts change speed together, which means that there is no refraction.

The effect of astronomical refraction where light is entering in the atmosphere- a more dense medium- is to make a celestial body appear higher in the sky that it otherwise would, and requires therefore a negative correction of the measured altitude. If a body is at the zenith, its light is not refracted. As the zenith distance increases, the refraction becomes greater and it can reach a value of up to half a degree if the body observed is at the horizon.

Refraction deviation angles **(R)** for an observer at sea level, for **apparent (rectified) altitude** angles of astronomical lines of sight **(ha)** through a standard atmosphere are shown in Appendix A.

In absence of a refraction deviation table, the actual refraction angle for **apparent (rectified) altitudes greater 10°**, can be estimated with tolerable accuracy using the following formula:

$$R \approx \frac{1}{tgha}$$

3225 Semi diameter (SD)

The semi diameter of a celestial body is half the angle, at the observers eye, subtended by the visible disk of the body. The position of the lower or upper limp of the Sun or the Moon with respect of the visible horizon can be judged with greater precision than that of the centre of the body. For this reason it is customary, when using a marine sextant and the visible horizon, to observe one of the limps of these two bodies and apply a correction for semi diameter. Normally the lower limp is used if it is visible (Ref. Figure 3225). In the case of gibbous or crescent Moon, however only the upper limp may be available.

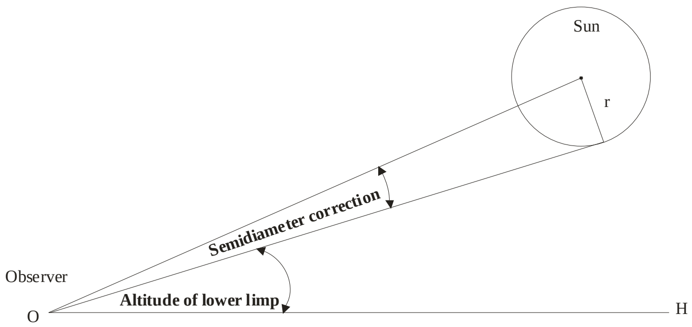


Figure 3225 Semi diameter

The semi diameter of the Sun varies from a little less than 15,7´ early in July, when the Earth is at its greatest distance from the Sun, to nearly 16,3´ early in January, when the Earth is nearest the Sun. In the nautical almanac the semi diameter of the Sun at UTC 12h for each day is given to the nearest 0,1´.

The variation in semi diameter of the Moon is greater, varying between about 14,7´ and 16,8´, and the values to be used for correcting the apparent altitude angle to the middle of the body are given in the nautical almanac to the nearest 0,1´.

The computed altitude of a body refers to the centre of that body. If the lower limp is observed, the sextant altitude is less than the altitude of the centre of the body and hence the correction is positive. If the upper limp is observed, the correction is negative. With a marine sextant semi diameter corrections are applied to observations of the Sun and the Moon, but not to other celestial bodies.

3226 Parallax (P)

Parallax is the difference in apparent position of a point as viewed from two different places. Considering the fact positions of celestial bodies are given relative to the centre of the Earth, while observations are made from its surface, the navigator should always keep in mind that there is a difference in apparent position from these two points called **geocentric parallax.**

If a body is in the zenith, at Z in Figure 3226, there is no parallax, for the line from the body to the centre of the Earth passes trough the observer.

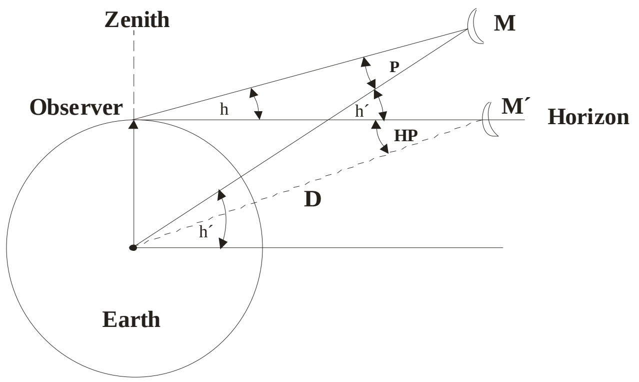


Figure 3226   Geocentric parallax

Suppose, however, the Moon is at **M**. From the position of the observer the Moon exhibits the elevation **h**, whilst from the centre of the Earth the true Moon elevation is **h´.** From the triangle formed by the lines, observer to the Moon, centre of the Earth to the Moon and the horizon, the equation h + P + (180°- h´) = 180° leads to **P = h´- h**. That is, the angle at the body between the lines to the observer and the centre of the Earth is equal to the difference in altitude at the two places and is called parallax in altitude **(P).** Because of the geocentric parallax, a body appears too low in the sky, and the **correction is always positive.**

The maximum value for a visible body occurs when that body is on the horizon, and this value is called **horizontal parallax (HP)**. With r the radius of the Earth and D the distance of the body from the centre of the Earth the horizontal parallax can be calculated by:

sinHP = r/D.

The nautical almanac provides information for the horizontal parallax for Moon and the planets Mars and Venus being close to the Earth.

The variation of the parallax in altitude **(P)** with reference to the horizontal parallax **(HP)** as exhibited in Figure 3226 above is: $0 \le P \le HP$. With known horizontal parallax, the parallax in altitude can be calculated as follows:

P = HP*cosh

3227 Summary of corrections

When extreme accuracy is desired, or at low altitudes where small changes in altitude result in significant changes in correction, the order of applying corrections to the sextant altitude **(hs)** to obtain the observed altitude **(ho)** shall be as shown below.

1	Sextant altitude		**hs**
2	Instrument correction	(+/-)	I
3	Index correction	(+/-)	IC
4	Dip [D = f(height of eyes in m)]	(-)	D [$D = 1{,}779\sqrt{he}$]
5	Sum 1 to 4 = Apparent altitude		**ha**
6	Refraction [R = f(ha)]	(-)	R
7	Semi diameter	(+/-)	SD
8	Sum 5 to 7 = Body elevation		**h**
9	Parallax in altitude [P = f(HP)] [P = HP*cosh]	(+)	P
10	Sum 8 to 9 = Observed altitude		**ho**

Example: 1) *On June 02 1975, the lower limp of the Sun is observed with a marine sextant having an IC of -2,0´ from a height of eye of 11,6 m. The sextant altitude is 51° 28,4´. Required: The observed altitude of the body.*

Answer:

hs =	*51°*	*28,4´*
IC =		*-2,0´*
D =		*-5,96´*
Ha =	*51°*	*20,44´*
R =		*-0,8´*
SD =		*+15,8´*
H =	*51°*	*35,4´*
ho=	***51°***	***35,4´***

Example: 2) *At about UTC 11 00 on June 02 1996, the lower limp of the Moon is observed with a marine sextant having an IC of +3,2´ from a height of eye of 9,75 m. The sextant altitude is 18° 4,6´. Required: The observed altitude of the body.*

Answer:

hs =	*18°*	*4,6´*
IC =		*+3,2´*
D =		*-5,46´*
Ha =	*18°*	*2,34´*
R =		*-2,9´*
SD =		*+16,5´*
H =	*18°*	*15,94´*
P =		*+57,45´*
ho=	***19°***	***13,4´***

3230 Quartz crystal marine chronometers and navigational calculators

Quartz crystal marine chronometers have replaced spring-driven chronometers aboard many ships because of their greater accuracy. They are maintained on GMT directly from radio time signals. This eliminates chronometer error (CE) and watch error (WE) corrections.

While not considered “instruments” in the strict sense of the word, certainly one of the professional navigator’s most useful tools is the navigational calculator or computer program. Calculators eliminate several potential sources of error in celestial navigation, and permit the solution of many more sights in much less time, making it possible to refine a celestial position much more accurately than is practical using mathematical or tabular methods.

PART 3

(Celestial navigation)

Chapter 3

(Almanacs)

3310 Introduction

Celestial navigation requires accurate predictions of the geographic position of the celestial bodies observed. These predictions are available from the almanacs yearly published by the national authorities. Although different types of almanacs are published, only the nautical almanac provides information specifically needed by marine navigators.

3320 Nautical almanac

The major portion of the Nautical almanac (Ephemerid tables) is devoted to hourly tabulation of the Greenwich Hour Angle (GHA) and declination, to the nearest 0,1´ of arc. Additional information is provided concerning the time equation, the Moon phases, corrections for use of the Polaris to determine the latitude of the observer, the visibility of the planets, the local mean time (LMT) of Sunrise and Sunset and the duration of the civil twilight at 0° longitude for latitudes from 70° N to 50° S, the LMT of Moonrise and Moonset for latitudes 70° N to 50° S, and increments and corrections used for interpolation of GHA and declination.

Example 1: *August the 13th 1990 and 07h 28´32´´ UTC, the navigator observes the Sun and the Moon at latitude 57° 25´N and longitude 007° 51´E. The LAH and the declination of the bodies is required.*

Answer: *From the almanac the following information can be extracted for the* ***Sun****:*

UTC=07h 00´ 00´´	*GHA=283° 46,4´*	*δ=14° 43,6´ N*
00h 28´32´´	*+7° 8´*	
Increment		*-0,4´*
UTC=07h 28´32´´	*GHA=290° 54,4´*	***δ=14° 43,2´ N***
Longitude	*+7° 51´*	
UTC=07h 28´32´´	***LHA=298° 45,4´***	
	-359° 60´	
	tE = 61° 14,6´	

From the almanac the following information can be extracted for the ***Moon****:*

UTC=07h 00´ 00´´	*GHA = 25° 11,2´*	*δ = 21° 25,6´ N*
00h 28´ 32´´	*+6° 48,5´*	
Increment	*+3,3´*	*+4,8´*
UTC=07h 28´ 32´´	*GHA = 32° 3´*	***δ=21° 30,4´ N***
Longitude	*+7° 51´*	
UTC=07h 28´ 32´´	***LHA = 39° 54´***	
	tW = 39° 54´	

Example 2: *June the 1st[h] 1990 and 07h 28´32´´ UTC, the navigator observes at latitude 24° 53´N and longitude 044° 26´W the Fomalhaut, the Saturn, the Wega and the Venus. The observations take place at 07h 57´51´´, at 07h 59´08´´, at 08h 00´33´´ and 08h 01´45´´. The LAH and the declination of the bodies is required.*

Answer: *From the almanac the following information can be extracted for the* ***Fomalhaut****:*

UTC=07h 00´ 00´´	*GHA (Aries) =354° 30,4´*	
00h 57´51´´	*+14° 30,1´*	
Fomalhaut	*SHA=+15° 42,8´*	*δ=29° 40,3´ S*
UTC=07h 57´51´´	*GHA= 384° 43,3´*	***δ=29° 40,3´ S***
Longitude	*-44° 26´*	
UTC=07h 28´32´´	***LHA= 340° 17,3´***	
	-359° 60´	
	tE = 19° 42,7´	

From the almanac the following information can be extracted for the ***Saturn****:*

UTC=07h 00´ 00´´	*GHA= 57° 51,2´*	*δ=21° 02,8´ S*
00h 59´08´´	*14° 47´*	
Increment	*+2,6´*	*+0,0´*
UTC=07h 28´32´´	*GHA= 72° 40,8´*	***δ=21° 2,8´ S***
Longitude	*-44° 26´*	
UTC=07h 28´32´´	***LHA= 28° 14,8´***	
	tW = 28° 14,8´	

From the almanac the following information can be extracted for the ***Wega****:*

UTC=08h 00´ 00´´	*GHA (Aries) = 9° 32,9´*	
00h 00´33´´	*+0° 08,3´*	
Wega	*SHA= +80° 50,6´*	*δ=38° 46,4´ N*
UTC=08h 00´33´´	*GHA= 90° 31,8´*	***δ=38° 46,4´ N***
Longitude	*-44° 26´*	
UTC=07h 28´32´´	***LHA= 46° 5,8´***	
	tW= 46° 5,8´	

From the almanac the following information can be extracted for the ***Venus****:*

UTC=08h 00´ 00´´	*GHA= 338° 47,6´*	*δ=10° 18,3´ N*
00h 01´45´´	*+0° 26,3´*	
Increment	*-0,0´*	*+0,0´*
UTC=07h 28´32´´	*GHA= 339° 13,9´*	***δ=10° 18,3´ N***
Longitude	*-44° 26´*	
UTC=07h 28´32´´	***LHA= 294° 47,9´***	
	-359° 60´	
	tE = 65° 12,1´	

3330 Long term nautical tables

In absence of an up to date almanac it is possible to obtain information concerning the GHA and the declination of the Sun, the GAH of the Aries, and the SHA and the declination of a selection of fixed stars with an accuracy sufficient for nautical navigation purposes. Said information can be extracted from supplementary tables included in the PUB. NO. 249 "Sight reduction tables for air navigation", published for the epoch of interest.

3331 GHA and declination of the Sun (Ref. Appendix E)

The main table of appendix E as well as its supplementary tables a, b, c and d make possible the determination of the GHA and δ of the Sun for any time during the years 1981-2016. The main table gives E (5° + Equation of Time) and declination of the Sun for the argument "Orbit Time" OT, the latter is formed by applying the h correction from table a to the nearest integral hour of GMT. In leap years, the upper value of the correction is to be used for January and February and the lower value for the rest of the year. Thus, OT´s corresponding to 1996 February 29d 16h 31´ GMT and March 1d 05h 29´ GMT are February 29d 09h 00´ and March 1d 21h 00´respectively.

Corrections to E and declination for OT are determined by entering Table b with the differences between consecutive values of E and of declination respectively as the horizontal argument, and with the number of hours of OT as the vertical argument. The declination differences are given in the main table.

The GAH is obtained by adding to the corresponding E the value of the diurnal arc obtained from Tables c and d. The latter two tables must be entered with argument GMT.

Example: *Find the GHA and declination of the Sun on 2001 January the 18th at 03h 30´35´´ UTC using the tables given in appendix E and compare the results with the values obtained from the Almanac for the year 2001.*

Answer: ***From the Appendix E*** *the following information can be obtained:*

OT = GMT (nearest integral hour) + Correction (table a)
= January the 18th 04h + 10h = January the 18th 14h.

		°	´	Diff.		°	´	Diff.	
Jan. 18th 00h OT,	*E =*	*2*	*28*	*(-5)*	*δ =*	*20*	*39*	*(-12)*	*S*
14h OT,			-3				- 7		
Jan. 18th 14h OT,	*E =*	*2*	*25*		***δ =***	***20***	***32***		***S***

For 03h 30´ GMT	*227*	*30*
For 00´35´´ GMT	*0*	*9*
Jan. 18th at 03h 30´35´´ **GHA = 230**		**04**

The GHA and the declination of the Sun extracted **from the Almanac** for the year 2001 are as follows:

UTC = 03h 00´ 00´´	*GHA = 222° 24,8´*	*δ =20° 32,7´ S*
00h 30´35´´	*7° 38,8´*	
Increment		*-0,3´*
UTC = 03h 30´35´´	***GHA = 230° 3,6´***	***δ = 20° 32,4´ S***

The differences of the results obtained from both data bases are negligible.

3332 GHA of the Aries (Ref. Appendix D)

Tables a, b and c of Appendix D enable for the determination of the GHA of the Aries at any time during the years 2001-2009. Table a gives GHA of the Aries at 00h UTC on the first day of each month. Table b gives the increment of GHA of the Aries for days and hours, and table c the increment for minutes and seconds.

Example: *Find the GHA of the Aries on 2001 April the 21st at 16h 35´23´´ UTC using the tables given in Appendix D and compare the results with the values obtained from the Almanac for the year 2010.*

Answer: ***From the Appendix D*** *the following information can be obtained:*

	Date	*hours*	*Min.*	*Sec.*	*GHA of the Aries*
1st Day of month					*189° 15´*
	21	*16*			*260° 22´*
			35	*23*	*8° 52´*
				GHA =	***98° 29´***

The GHA of the Aries extracted **from the Almanac** for the year 2001 is as follows:

UTC =16h 00´ 00´´	*GHA = 89° 37,2´*
00h 35´ 23´´	*8° 52,2´*
	GHA = 98° 29,4´

The differences of the results obtained from both data bases are again negligible.

3333 SHA and declination of navigational stars (Ref. Appendix B)

The main table of Appendix B provides data for SHA and the declination of selected navigational stars for the epoch of interest.

3340 Meridian transit of a body (Culmination)

If a body passes during its apparent movement around the Earth through the meridian of the observer, the body culminates at that particular geographical position. This transit occurs twice during the rotation of the body around the Earth, as the body passes the "upper" and the "lower" meridian of the observer, and said transits are called the **"Upper Culmination"** and the **"Lower Culmination"**. The LHA in the first case is 000° 00´, and in the second case 180° 00´. At the culminations the body reaches its maximum respectively minimum altitudes.

It should be noted that the lower culmination of a body is not necessarily visible from any geographical position, unless the body is circumpolar. Circumpolar is a body if its declination is greater than the complement of the latitude of the observer and has the same name as said latitude.

Example 1: *Find the minimum latitude from which Wega still appears as a circumpolar body.*

Answer: *According to* ***Appendix B*** *the declination of Wega is* $\delta = 38° 48´N$. *Wega appears still as a circumpolar body at a latitude where* $\delta > 90 - \varphi$.
The minimum latitude is therefore: $\varphi > 90 - \delta > 51° 12´N$

Example 2: *Find the minimum latitude from which at summer solstice the lower culmination of the Sun is still visible.*

Answer: *According to* ***Appendix E*** *the declination of the Sun at the summer solstice is* $\delta = 23° 26´ N$.
The Sun is therefore visible at a minimum latitude of $\varphi > 90 - \delta > 66° 34´ N$

Example 3: *Find the time of the Local Apparent Noon* ***(LAN)*** *at latitude 56° 20´N and longitude 19° 20´E October the 20th 2001 using the data basis provided in Appendix E and compare the results with those to be obtained from the Almanac applicable for the year 2001.*

Answer: ***From the Appendix E*** *the following information can be obtained:*
As the nearest integral hour for the meridian transit of the Sun at Greenwich we use 12h 00´UTC

OT = GMT (nearest integral hour) + Correction (table a)
= October the 20^{th} 12h + 10h = October the 20^{th} 22h.

		°	´	Diff.	°	´
Oct. 20^{th} 00h OT,	*E =*	*8*	*46*	*(+2)*		
22h OT,			+2			
Oct. 20^{h} 22h OT,	*E =*	*8*	*48*		*8*	*48*
For 11h 00´ GMT		*340*	*00*			
For 12h 00´´ GMT					*355*	*00*
Oct. 20^{th} at 11h 00´00´´	**GHA =**	**348**	**48**			
Oct. 20^{th} at 12h 00´00´´				**GHA =**	**003**	**48**

$$\Delta T = \frac{360° - 348{,}8}{363{,}8 - 348{,}8} * 60 = 44{,}8´$$

*The transit at Greenwich occurs at **11h 44´ 48´´ UTC.***
*At the longitude of the observer the meridian transit of the Sun occurs 01h 17´ 19´´ (19,33° /15) earlier than in Greenwich. **LAN** at the observers position is therefore at **10h 27´ 29´´ UTC**.*

*According to the **Almanac** for the year 2001 on October the 20^{th} the Sun culminates at 11h 45´UTC at Greenwich. At the longitude of the observer the meridian transit of the Sun occurs 01h 17´ 19´´ (19,33° /15) earlier than in Greenwich. **LAN** at the observers position is therefore at **10h 27´ 41´´ UTC**.*

Example 4: *Find time of the meridian transit of the Moon at latitude 49° 57´N and longitude 4° 12´ W in the morning of June the 17^{th} 2001.*

Answer: *According to the **Almanac** the Moon culminates June the 17^{th} in Greenwich at 08h 28´ UTC, and June the 18^{th} at 09h 15´ i.e. 47´later. The time difference of the culmination at longitude 4,2° W is therefore:*

$$\Delta t = \frac{4{,}2}{360} * 47 = 0{,}55´$$

*and the Moon culmination occurs at **08h 28´ 33´´ UTC**.*

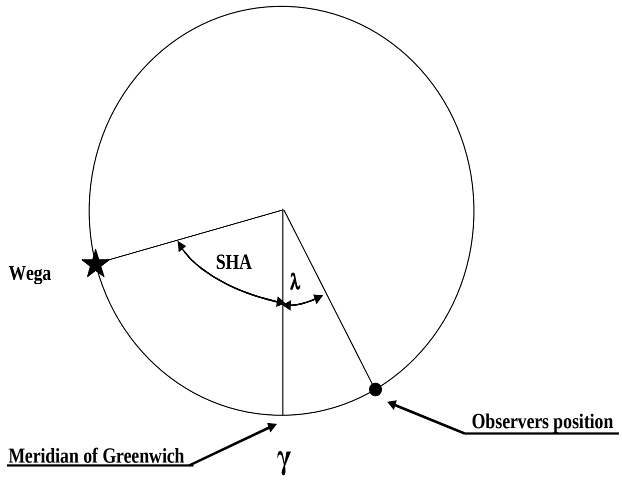
Example 5: *Find time of the meridian transit of Wega at longitude 006° 30´ E in the afternoon of September the 29th 2010 using the data basis provided in Appendices B and D.*

Answer: *The Greenwich meridian transit of Aries can be found using the data base exhibited in **Appendix D** as follows:*

Date	*Days*	*Hours (UTC)*	*GHA of Aries*
September the 1st	*0*	*00*	*340° 03´*
	29	*23*	*13° 33´*
	29	*24*	*28° 35´*
September the 29th		*23*	*353° 36´*
“		*24*	*368° 38´*

$$\Delta T = \frac{360° - 353{,}6}{368{,}6333 - 353{,}6} * 60 = 25{,}5432´$$

The Greenwich meridian transit of Aries occurs at 23h 25´ 33´´



From the above figure it is obvious that the meridian transit of Wega at the observer’s position occur ΔT=LHA/15=SHA+ λ hours earlier than the culmination of the Aries at Greenwich:

***Appendix B** exhibits a sidereal hour angle for Wega of: SHA=80° 41´.*

$$\Delta T = \frac{LHA}{15} = \frac{SHA + \lambda}{15} = \frac{80{,}6833° + 6{,}5°}{15} = 5{,}8122h$$

The meridian transit of Wega at the observer’s position occurs therefore at:

22h 84´ 93´´ UTC
-5h 48´ 44´´ UTC

17h 36´ 49´´ UTC

PART 3

(Celestial navigation)

Chapter 4

(Sight reduction)

3410 Basic procedures

Irrespective whether the navigator is using tables or handheld calculators, reducing a celestial sight to obtain a line of position consists of the following steps:

- Correct the **sextant altitude (hs)** to obtain **observed altitude (ho)**.
- Determine the body's **Greenwich hour angle (GHA)** and **declination (δ)**.
- Select an **assumed position (AP)** and find its **local hour angle (LHA).**
- Compute **altitude (hc)** and **azimuth (Zn)** for the assumed position.
- Compare the computed and observed altitudes.
- Plot the line of position.

3420 Plotting the line of position

Sight reduction reduces the problem of scale to manageable size. Depending on a body's altitude its **geographic position (GP)** could be thousands of miles from the observer's position and can therefore not be plotted on the chart.

To eliminate this problem the navigator chooses an assumed position near but not necessarily coincident with his dead reckoning position. He chooses latitude and longitude of the assumed position to correspond to the entering arguments of LHA and latitude used in Pub. 229. From the Pub. 229 the navigator extracts the computed altitude and the direction from GP to AP. If the navigator is using a handheld calculator instead of Pub. 229, he chooses his DR position as the AP to calculate hc and Zn.

The navigator has now enough information to plot the line of position. All he has to do is to determine the difference between hc and ho and to plot the altitude intercept in the Zn direction in accordance with the rules derived from the Figure 3420 below.

- The altitude intercept is the difference in length of the radii of the circles of equal altitude passing through the assumed position of the observer and the observer's actual position.

- The position having the greater altitude is on the circle of smaller radius and is therefore closer to the observed body's geographical position (GP).

- Express the altitude intercept in nautical miles and labelled it **(T)** or **(A)** to indicate whether the line of position is **towards** or **away** from the geographical position of the body observed, as measured from AP.

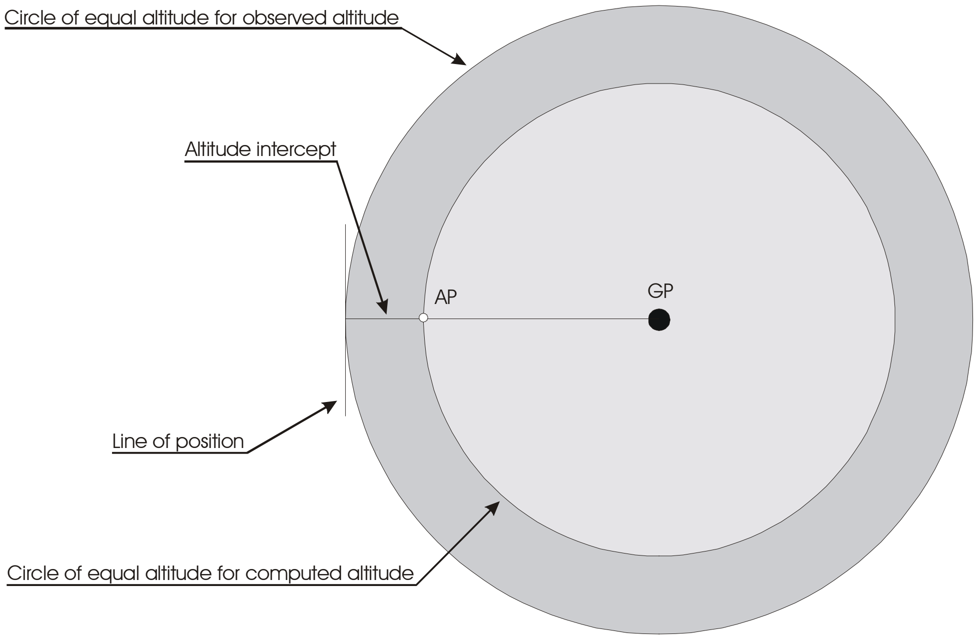


Figure 3420 Line of position from a celestial observation

In the Figure 3420 above AP is shown in the inner circle. Therefore hc is greater than ho. As a consequence the line of position intersects a point measured from the AP away from GP a distance equal to the altitude intercept.

3430 The celestial triangle

A triangle formed by arcs of great circles of a sphere is called a spherical triangle. As in this particular case the spherical triangle on Figure 3430 is formed on the celestial sphere, the triangle is called celestial triangle.

- The celestial triangle in Figure 3430 is shown on the plane of the celestial meridian.
- The Earth is at the centre O.
- The body is at S.
- The arc P on the hour circle is the pole distance of the body and its complement to 90° is the declination (δ) of the body.
- The arc Z on the vertical circle is the zenith distance of the body and its complement to 90° is the altitude (h) of the body.
- The arc B on the celestial meridian between the zenith of the observer (Z) and the elevated pole (Np) is the so called zenith pole distance and its complement is the latitude of the observer.
- The angle at the zenith, having the vertical circle and that arc of the celestial meridian, which includes the elevated pole, as sides, is the azimuth angle.
- The angle at the elevated pole having the celestial meridian and the hour circle as sides is the meridian angle.

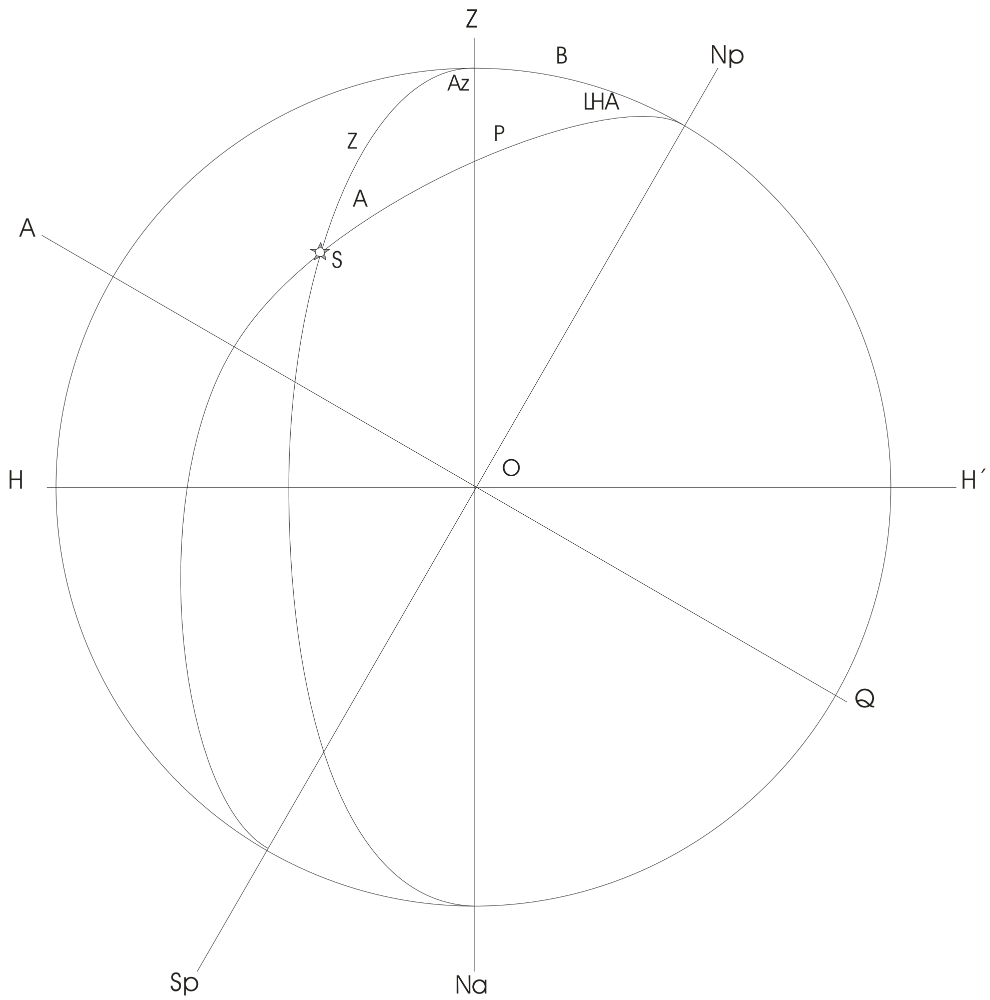


Figure 3430 The celestial triangle

3440 Mathematical solutions of the celestial triangle.

In order to be able to solve various navigation problems like establishing a line of position, identification of an unknown celestial body, calculation of azimuths at known altitudes, find initial great circle courses etc. it is important to be able to provide solutions for the celestial triangle using the spherical trigonometry equations outlined below.

$$(1)\ \frac{\sin A}{\sin B} = \frac{\sin Az}{\sin P} = \frac{\sin LHA}{\sin Z}$$

(2) cosP= cosB*cosZ+sinB*sinZ*cos Az

(3) cosZ= cosB*cosP+sin B*sinP*cosLHA

(4) cosB= cosZ*cosP+sinZ*sinP*cosA

Substitution of Z, B and P in equation (3) above by their complement angles, lead to the following equation.

$$\cos(90-h) = \cos(90-\varphi) * \cos(90-\delta) + \sin(90-\varphi) * \sin(90-\delta) * \cos LHA$$

Respectively: (5) $\sinh = \sin\varphi * \sin\delta + \cos\varphi * \cos\delta * \cos LHA$

Substitution of P, B and Z in equation (2) above by their complement angles, lead to the following equation.

$$\cos(90-\delta) = \cos(90-\varphi) * \cos(90-h) + \sin(90-\varphi) * \sin(90-h) * \cos Az$$

Respectively: (6) $\sin\delta = \sin\varphi * \sinh + \cos\varphi * \cosh * \cos Az$

Substitution of P and Z in equation (1) above by their complement angles, lead to the following equation.

$$\frac{\sin Az}{\sin(90-\delta)} = \frac{\sin LHA}{\sin(90-h)}$$

Respectively: (7) $\cosh = \dfrac{\sin LHA * \cos\delta}{\sin Az}$

Substituting in equation (6) "sinh" by equation (5) and "cosh" by equation (7), one gets:

$$\sin\delta = \sin\varphi * (\sin\varphi * \sin\delta + \cos\varphi * \cos\delta * \cos LHA) + \cos\varphi * \frac{\sin LHA * \cos\delta}{\sin Az} * \cos Az$$

Respectively: (8) $tgAz = \dfrac{\sin LHA}{\cos\varphi * tg\delta - \sin\varphi * \cos LHA}$

Equations (5) and (8) above enable us to calculate the expected Azimuth and altitude of the body at the observers assumed position as follows:

Computed altitude $hc = \arcsin[\sin\varphi * \sin\delta + \cos\varphi * \cos\delta * \cos LHA]$

Computed Azimuth $Az = arctg\dfrac{\sin LHA}{\cos\varphi * tg\delta - \sin\varphi * \cos LHA}$ → Zn = {Az}

N E

S W

↑ ↑

φ t

Rules for computation of hc and Zn.

- When φ and δ are of contrary name δ is treated as a negative quantity.
- When LHA is greater than 180° LHA is treated as a negative quantity.

- When Az is negative, the reference from which Zn starts counting has a name contrary to name of the latitude.

- Zn is counting from its north or south reference to the amount defined by Az to an east or west direction depending on the name of the meridian angle t.

Example : *On August the 11th 1957, the 08:00 ZT dead reckoning position of a vessel is lat. 45° 45´N, long. 08° 25´W. The Vessel is on course 034°, speed 7,5 knots. At 09:00:26 UTC the lower limp of the Sun is observed from a height of 3 m with a sextant having an index correction of (-)3´. The observed altitude is hs=35° 22´.*
In order to get a fix the navigator observes again the lower limp of the Sun at its local apparent noon and obtains hs=59° 06´. Find the position of the vessel at the LAN of the Sun.

Answer:

hs =	*35°*	*22´*	
IC=		*-3´*	
D=		*-3,08´*	*(Ref. § 3227)*
ha=	*35°*	*15,92´*	
R=		*-1,4´*	*(Ref. Appendix A)*
SD=		*15,8´*	*(Ref. Almanac)*
h=	*35°*	*30,32´*	
P=		*0´*	
ho=	***35°***	***30,32´***	

From the almanac the following information can be extracted for the Sun:

09h 00´ 00´´	*UTC*	*GHA = 313°*	*42,9´*	*δ = 15° 18,7´ (0,7) N*
00h 00´ 26´´	*UTC*		*+6,5´*	*0,0*
09h 00´ 26´´	*UTC*	*GHA = 313°*	*49,4´*	***δ = 15° 18,7´ N***
		λg1 = 8°	*25´ W*	
		LHA = 305°	***24,4´ (tE)***	

The altitude and the azimuth of the body are calculated as follows:

*hc=arcsin[sinφ*sinδ+cosφ*cosδ*cosLHA]=arcsin[sin(45,75)*sin(15,3117)+ cos(45,75)*cos(15,3117)* cos(-305,4067)] = 35,3861°*

hc = 35° 23,18´

*Az = acrtg{sinLHA / [cosφ*tgδ-sinφ*cosLHA]} = arctg{sin(305,4067) / [cos(45,75)* tg(15,3117)-sin(45,75)*cos(-305,4067)]} = -74,6° = S 74,6 E*

Zn = 105°

Δh = ho-hc = T 7,14 Sm along Zn (ho>hc)

The line of position of the vessel during the first observation is drawn as LOP1 in the figure below.

According to the almanac the meridian transit of the Sun in Greenwich occurs at 12:05 UTC. As the navigator expects the local culmination of the Sun, if the *vessel reaches a longitude of approximately 08° W, the local meridian transit of the Sun will be at 12:05 + 8/15 = 12:37 UTC i.e. at approximately 11:37 ZT. From 08:00 up to 11:37 the vessel moves 7,5 Kn*3,6 h = 27 Sm.*

The Sun is observed during its local apparent noon at the following altitude:

hs =	*59°*	*06´*	
IC=		*-3´*	
D=		*-3,08´*	*(Ref. § 3227)*
ha=	*58°*	*59,92´*	
R=		*-0,6´*	*(Ref. Appendix A)*
SD=		*15,8´*	*(Ref. Almanac)*
h=	*59°*	*15,12´*	
P=		*0´*	
ho=	***59°***	***15,12´***	

The declination of the Sun during its local apparent noon can be obtained from the almanac as follows:

12h	*00´*	δ *= 15°*	*16,5´(0,7) N*
00	*37´*		*-0,35´*
12h	*37´ UTC*	$\boldsymbol{\delta}$ ***= 15°***	***16,15´ N***

The latitude of the vessel at the LAN can be calculated as follows:

$\varphi = 90\text{-}ho + \delta = 90 - 59{,}262 + 15{,}2692 = 46{,}0072°$

$\boldsymbol{\varphi = 46° \ \ 0{,}4´ \ N}$

The latitude of the vessel is drawn as LOP2 in the figure below. Advancing the LOP1 from AP1 to AP2 provides a position fix in the chart.

However from the drawing sheet used below only the latitude can directly be extracted. Determination of the longitude requires the calculation of the departure.

The $\Delta\varphi$ *if a vessel sails from AP1 on course 34°, 27 Sm to AP2 is:*

$\Delta\varphi = 27*\sin(90-34) = 22{,}4$ *Sm*

The latitude atAP2 is:

$\boldsymbol{\varphi(AP2) = \varphi(AP1) + \Delta\varphi = 45° \ \ 45´ + 22{,}4´ = 46° \ \ 7{,}4´ \ \ N}$

The mid latitude between AP1 and AP2 is:

$\varphi m = 45° \ 45´ + \Delta\varphi / 2 = 45{,}94°$

The departure from AP1 to AP2 on this course is:

$p(AP2) = 27*\cos(90-34) = 15{,}1$ *Sm*

The difference in longitude between AP1 and AP2 is:

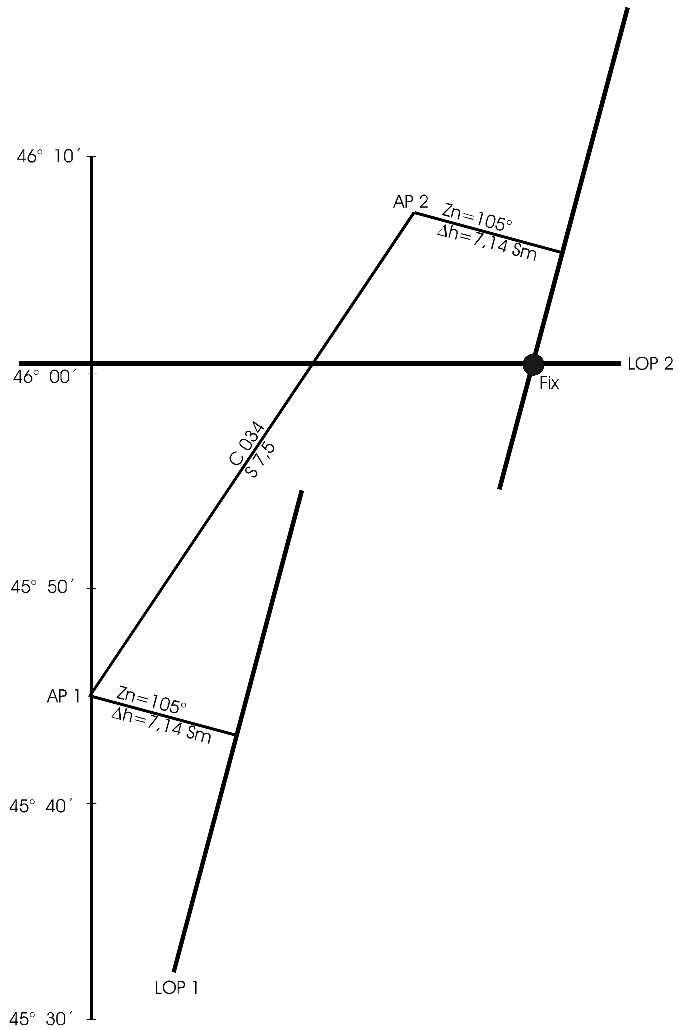
$\Delta\lambda(AP2) = p(AP2) / \cos \varphi m = 21{,}7´$

The longitude at AP2 is therefore:

$\boldsymbol{\lambda(AP2) = \lambda(AP1) + \Delta\lambda = 08° \ \ 25´ - 21{,}7´ = 08° \ \ 3{,}3´ \ W}$

The assumed position of the vessel during the transit of the Sun trough the local meridian is:

$\boldsymbol{\varphi(AP2) = 46° \ \ 7{,}4´ \ N \ / \ \lambda(AP2) = 08° \ \ 3{,}3´ \ W}$



The departure from AP1 to the fix extracted from the figure above is:

p(fix) = 20,7 Sm

The difference in longitude between AP1 and the fix is:

$\Delta\lambda(fix) = p(fix) / \cos\varphi = 20{,}7\ Sm / \cos 46{,}0072° = 29{,}8´$

The longitude of the fix is therefore:

$\boldsymbol{\lambda(fix) = \lambda(AP1) + \Delta\lambda(fix) = 08°\ \ 25´ - 29{,}8´ = 07°\ \ 55{,}2´\ W}$

The position of the vessel during the transit of the Sun trough the local meridian is:

$\underline{\boldsymbol{\varphi = 46°\ \ 0{,}4´\ N\ /\ \lambda = 07°\ \ 55{,}2´\ W}}$

3450 Solutions of the celestial triangle using the sight reduction tables for marine navigation HO 229

This six-volume series of **Sight Reduction Tables for Marine Navigation** is designed to facilitate the practice of celestial navigation at sea.
The tabular data are the solutions of the navigational triangle of which two sides and the included angle are known and it is necessary to find the values of the third side and adjacent angle.

3451 Description of the tables

The tables are divided into six volumes, each of which includes two eight-degree zones of latitude. An overlap of 1° occurs between volumes. The six volumes cover latitude bands 0° to 15°, 15° to 30°, 30° to 45°, 45° to 60°, 60° to 75° and 75° to 90°.
Each consecutive opening of the pages of a latitude zone differs from the preceding one by 1° of local hour angle (LHA), whilst the values of LHA are prominently displayed at the top and bottom of each page.

The horizontal argument heading each column is latitude, and the vertical argument is declination. For each combination of arguments, the tabulations are, the computed altitude (hc), the altitude difference (d) with its sign, and the azimuth angle (Z).

Within each opening, the data on the left-hand page are the altitudes, altitude differences, and azimuth angles of celestial bodies when the latitude of the observer has the same name as the declinations of the bodies. For any LHA tabulated on a left-hand page and any combination of the computed latitude and declination arguments, the computed altitude and associated azimuth angle respondents on the left-hand page are those of a body above the celestial horizon of the observer. The LHA's tabulated on the left-hand pages are limited to the following ranges: 0° increasing to 90° and 360° decreasing to 270°.

On the right-hand page of each opening, the data above the horizontal rules are the computed altitudes, altitude differences, and azimuth angles of celestial bodies above the celestial horizon when the latitude of the observer has a name contrary to the name of the declinations of the bodies and the LHA's of the bodies are those tabulated at the top of the page. The data below the horizontal rules are the computed altitudes, altitude differences, and azimuth angles of celestial bodies above the celestial horizon when the latitude of the observer has the same name as the declinations of the bodies and the LHA's of the bodies are those tabulated at the bottom of the page.

The LHA's tabulated at the top of a right-hand page are the same as those tabulated on the left-hand page of the opening. The LHA's tabulated at the bottom of the right-hand page are limited to the range 90° increasing to 270°, one of the two LHA's at the bottom of the page is in the range 90° increasing to 180°, the other LHA is in the range 180° increasing to 270°, the LHA in the range 90° increasing to 180° is the supplement of the LHA at the top of the page in the range 0° increasing to 90°. When the LHA is 90°, the left and right-hand pages are identical.

3452 Interpolation tables.

Interpolation tables for declination Increments are included on each volume of the publication as follows:

- Declination increments from 0,0´ to 31,9´ on the inside front cover
- Declination Increments from 28,0´ to 59,9´on the inside back cover

Chapter B of each volume of the publication contains explanations for use of the interpolation tables. However up to a computed altitude of 60° the influence of the declination increment to the altitudes can be found by a pure linear interpolation. In this case, the required interpolation can be effected by multiplying the altitude difference (a first difference) by the excess of the actual declination over the integral declination argument divided by 60´.

Example : *On June the 2nd 1975, the 17:42 ZT dead reckoning position of a vessel is lat. 41° 10´ S, long. 128° 00´ E. The Vessel is on course 315°, speed 20 knots. Observations are made from a height of 9,45 m with a sextant having an index correction of (-)1as follows:*

Body	***UTC***	***Sextant altitude***	
Spica	*08:24:03*	*32°*	*30,4´*
Regulus	*08:29:58*	*36°*	*57,1´*
Procyon	*08:35:59*	*35°*	*05,1´*
Canopus	*08:41:55*	*52°*	*47,7´*

Determine the 17:42 fix using the Pub. No. 229.

Answer: *Information for the sidereal hour angle and the associated declination of each body are extracted from the almanac as follows:*

Body	***SHA***		***Declination***	
Spica	*159°*	*01,1´*	*11°*	*02,2´ S*
Regulus	*208°*	*13,9´*	*12°*	*05,2´ N*
Procyon	*245°*	*29,8´*	*05°*	*17,2´ N*
Canopus	*264°*	*09,3´*	*52°*	*14,1´ S*

The observed altitudes of the bodies are:

	Spica		***Regulus***		***Procyon***		***Canopus***	
hs =	*32°*	*30,4´*	*36°*	*57,1´*	*35°*	*05,1´*	*52°*	*47,7*
IC=		*-1,0´*		*-1,0´*		*-1,0´*		*-1,0´*
D=		*-5,47´*		*-5,47´*		*-5,47´*		*-5,47*
ha=	*32°*	*23,93´*	*36°*	*50,63´*	*34°*	*58,63´*	*52°*	*41,23´*
R=		*-1,55´*		*-1,36´*		*-1,4´*		*-0,75´*
SD=		*00,0´*		*00,0´*		*00,0´*		*00,0´*
h=	*32°*	*22,38´*	*36°*	*49,27´*	*34°*	*57,23´*	*52°*	*40,48´*
P=		*00,0´*		*00,0´*		*00,0´*		*00,0´*
ho=	***32°***	***22,38´***	***36°***	***49,27´***	***34°***	***57,23´***	***52°***	***40,48´***

*With nearest latitude of **41° S**, the values for the assumed longitudes, the altitude intercepts and the Azimuths for the individual bodies are calculated below:*

	Spica			***Regulus***	
GHA γ for 8h UTC	*010°*	*10,3´*		*010°*	*10,3´*
Increment for 24m03s	*006°*	*1,7´*	*29m58s*	*007°*	*30,7´*
SHA of the body	*159°*	*01,1´*		*208°*	*13,9´*
GHA of the body	*175°*	*13,1´*		*225°*	*54,9´*
aλ	***127°***	***46,9´***		***128***	***05,1´***
LHA of the body	*303°*	*00,0(tE)*		*354°*	*00,0´(tE)*
hc for δ=11°	*31°*	*55,0´*	*12°*	*36°*	*42,6´*
increment for δ=2,2´		*+1,5´*	*05,2´*		*-5,2´*
hc for δ=11° 02,2´	*31°*	*56,5´*	*12° 05,2´*	*36°*	*37,4´*
ho	*32°*	*22,38´*		*36°*	*49,27´*
ΔH	**25,9 Sm (T)**			**11,9 Sm (T)**	
Z for *δ=11°*	*104,1°*		*12°*	*172,7°*	
increment for 2,2´	*-0,03°*		*05,2´*	*0,0°*	
Z for δ=11° 02,2´	*S104,1E*		*12° 05,2´*	*S172,7E*	
Zn	***075,9°***			***007,3°***	

	Procyon			***Canopus***	
GHA γ for 8h UTC	*010°*	*10,3´*		*010°*	*10,3´*
Increment for 35m59s	*009°*	*1,2´*	*41m55s*	*010°*	*30,5´*
SHA of the body	*245°*	*29,8´*		*264°*	*09,3´*
GHA of the body	*264°*	*41,3´*		*284°*	*50,1´*
aλ	***128°***	***18,7´***		***128***	***09,9´***
LHA of the body	*33°*	*00,0(tW)*		*52°*	*00,0´(tW)*
hc for δ=05°	*34°*	*59,1´*	*52°*	*52°*	*48,5´*
increment for δ=17,2´		*-14,9´*	*41,1´*		*+2,6´*
hc for δ=05° 17,2´	*34°*	*44,2´*	*52° 41,1´*	*52°*	*51,1´*
ho	*34°*	*57,23´*		*52°*	*40,48´*
ΔH	**13 Sm (T)**			**10,6 Sm (A)**	
Z for *δ=05°*	*138,5°*		*52°*	*054,4°*	
increment for δ=17,2´	*-0,172°*		*41,1´*	*-1,096°*	
Z for δ=11° 02,2´	*S138,7W*		*52° 41,1´*	*S053,3W*	
Zn	***318,7°***			***233,3°***	

The plotting sheet below illustrates the graphical interpretation of the results obtained above.

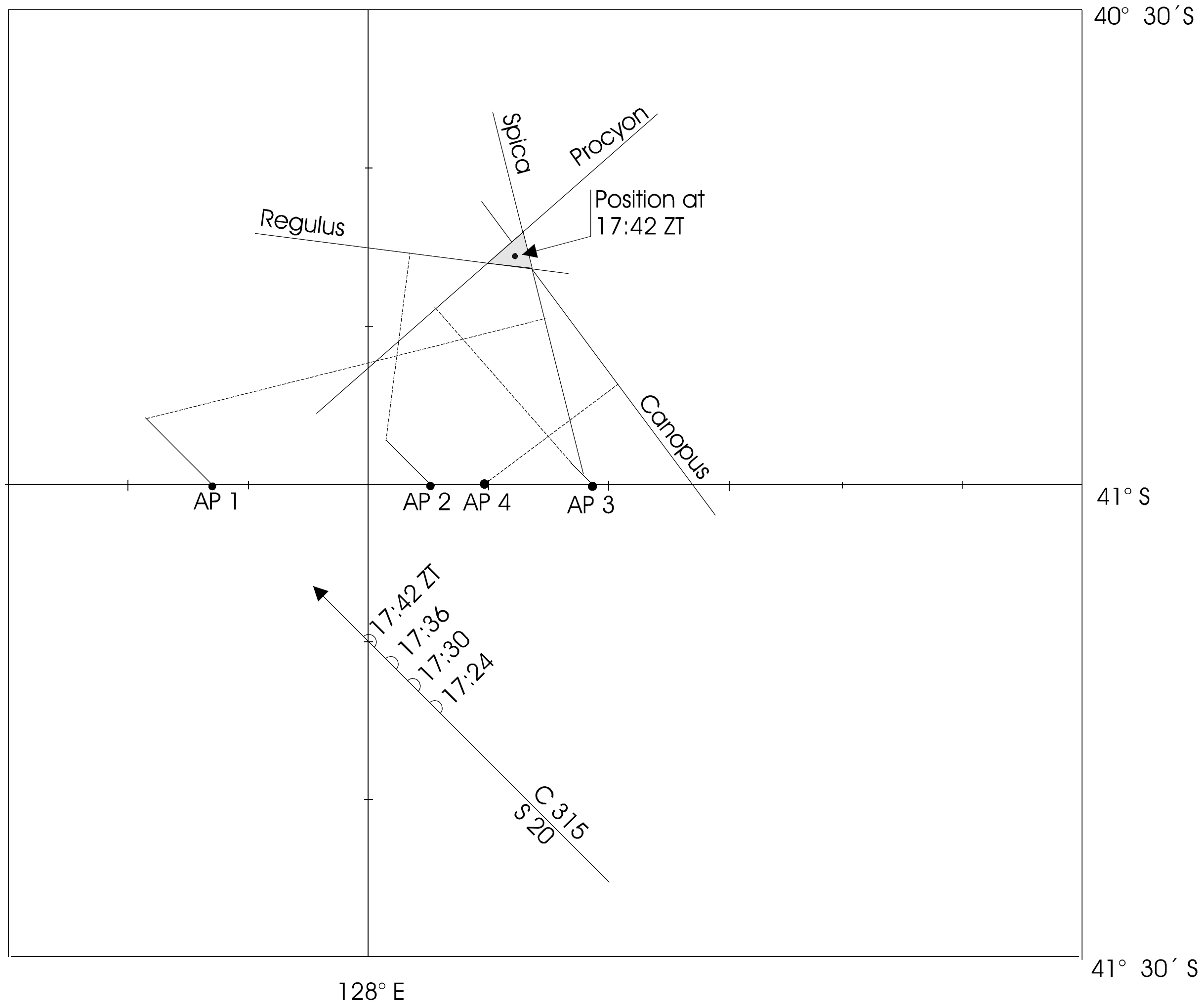
In the lower part of the drawing, the dead reckoning positions of the vessel are indicated at which the observations of the four bodies have been made.

At the nearest latitude of 41° S the assumed positions AP1 to AP4 are shown. In order to satisfy the entry requirements of Publication No. 229, the longitudes of said positions have been selected in such a way that the associated LHS´s become whole degrees.

Due to the fact the fix is required at 17:42 ZT, the assumed positions AP1 to AP4 have been advanced by a distance obtained from the speed of the vessel (20 Kn) and the difference between the times of the various observations and the time of the fix, in the direction of the course of the vessel (315°)

Plotting Δh in the direction of Zn for each individual body, we obtain the 4 lines of position marked with the names of the observed bodies. The vessels position at 17:42 ZT can be extracted from the area where the 4 LOP´s are coming together.

φ = 40° 45,6´ S / λ = 128° 12,3´ E



PART 3

(Celestial navigation)

Chapter 5

(Specific solutions of the celestial triangle)

3510 Horizon, Transit time, Sunrise, Sunset, and twilight definitions

3511 Horizon

Whatever the location of the observer, on or near the Earth's surface, the Earth is perceived as a plane. The sky resembles one-half of a sphere or dome centred at the observer. If there are no visual obstructions, the apparent intersection of the sky with the Earth's (plane) surface is the horizon, which appears as a circle centred at the observer. For rise/set computations, the observer's eye is considered to be **on the surface of the Earth**, so that the horizon is geometrically exactly **90 degrees from the observer's zenith**.

3512 Transit time

The transit time of a celestial body refers to the instant that its centre crosses the observer's meridian. For observers in low to middle latitudes, **transit is approximately midway between rise and set**, and represents the time at which the body **is highest in the sky**. At high latitudes, neither of these statements may be true - for example, there may be several transits between rise and set.

3513 Sunrise and Sunset

Excluding circumpolar objects, celestial bodies – stars and planets included – seem to appear in the sky at the horizon to the East of any particular place, then to cross the sky and again disappear at the horizon to the West. Because the Sun appears as circular disk and not as a point of light, a definition of rise or set must be very specific.

Sunrise or sunset is defined to occur when the geometric zenith distance of centre of the Sun is:

$$Z = 90.8333°$$

That is, the centre of the Sun is geometrically **50 arc minutes** below a horizontal plane. For an observer at sea level with a level, unobstructed horizon, under average atmospheric conditions, **the upper limb of the Sun will then appear to be tangent to the horizon**. The 50-arcminute geometric depression of the Sun's centre used for the computations is obtained by adding the average apparent radius of the Sun (16 arc minutes) to the average amount of atmospheric refraction at the horizon (34 arc minutes).

Computed sunrise and set times **may be in error by a minute or more**, because, in practice, they are depending upon unpredictable atmospheric conditions that affect the amount of refraction at the horizon. Additionally the accuracy of rise and set computations decreases at high latitudes. There, small variations in atmospheric refraction can change the time of rise or set **by many minutes**, since the Sun and Moon intersect the horizon at a very shallow angle. It is not practical to attempt to include such effects in routine rise/set computations.

3514 Twilight

Before sunrise and again after sunset there are intervals of time, twilight, during which there is natural light provided by the upper atmosphere, which does receive direct sunlight and reflects part of it toward the Earth's surface. The major determinants of the amount of natural light during twilight are the state of the atmosphere generally and local weather conditions in particular.

Atmospheric conditions are best determined at the actual time and place of events. Nevertheless, it is possible to establish useful, though necessarily approximate, limits applicable to large classes of activities by considering only the position of the Sun below the local horizon. Reasonable and convenient definitions have evolved. There are three kinds of twilight defined: **civil** twilight, **nautical** twilight, and **astronomical** twilight.

35141 Civil twilight

Civil twilight is defined to begin before sunrise and ends after sunset when the geometric zenith distance of the centre of the Sun is geometrically 6 degrees below the horizon i.e.

$$Z = 96°$$

This is the limit at which **twilight illumination is sufficient**, under good weather conditions, **for terrestrial objects to be clearly distinguished**. Under good atmospheric conditions and in the absence of moonlight or other illumination, at the beginning of morning civil twilight, or end of evening civil twilight, the horizon is clearly defined and the brightest stars are visible. This is not the case in the morning before the beginning of civil twilight and in the evening after the end of civil twilight.

35142 Nautical twilight

Nautical twilight is defined to begin in the morning, and to end in the evening, when the geometric zenith distance of the centre of the sun is geometrically 12 degrees below the horizon i.e.

$$Z = 102°$$

At the beginning or end of nautical twilight, under good atmospheric conditions and in the absence of other illumination, general outlines of ground objects may be distinguishable. The illumination level is such that **the horizon is still visible** even on a Moonless night allowing mariners to **take reliable star sights for navigational purposes**, hence the name.

35143 Astronomical twilight

Astronomical twilight is defined to begin in the morning, and to end in the evening, when the geometric zenith distance of the centre of the sun is geometrically 18 degrees below the horizon i.e.

$$Z = 108°$$

Before the beginning of astronomical twilight in the morning and after the end of astronomical twilight in the evening, **scattered light from the Sun is less than that from starlight** and other natural sources. For a considerable interval after the beginning of morning twilight and before the end of evening twilight, sky illumination is so faint that it is practically imperceptible.

3520 Find the latitude at the meridian passage of the Sun [Local Apparent Noon (LAN)]

The azimuth of the Sun (Zn) at the local apparent noon is 180° for north latitudes and 0° for south latitudes.

From the figure 3510 below the relationship $ho - \delta + \varphi = 90°$ can be extracted and it can be use to calculate the latitude at LAN as shown below:

If latitude and declination are of the same name: $\varphi = (90 + \delta) - ho$

If latitude and declination are of different name: $\varphi = (90 - \delta) - ho$

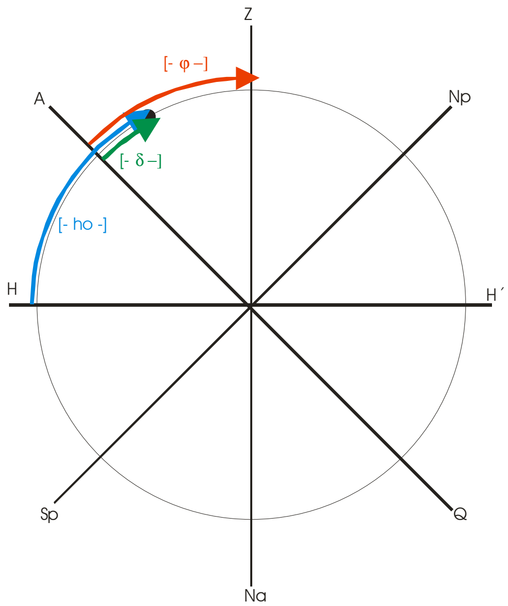


Figure 3520 Local Apparent Noon

Example : *June the 17th 2001 at dead reckoning position 44° 21´N and 14° 14´W the lower limp of the Sun at its southern meridian transit is observed. The observation data are: hs=68° 47´; IC=-2´; he = 3 m. Find the latitude of the observer using A) the data basis provided in* ***Appendix E*** *and B) compare the results with those obtained by means of the almanac.*

Answer: ***A) Solution using Appendices A and E****:*

According to §3225 the semi diameter of the Sun varies between 15,7´(early July) and 16,3´(early January).For this particular case it is assumed that SD=15,7´. The observed altitude of the body is calculated as follows:

hs =	*68°*	*47´*
IC =		*-2´*
D =		*-3,08´*
Ha =	*68°*	*41,92´*
R =		*-0,45´*
SD =		*15,7´*
H =	*68°*	*57,17´*
P =		*0´*
Ho =	***68°***	***57,17´***

For the declination of the Sun 12h GMT will be assumed to be the nearest integral hour to the orbit time.

OT = GMT (nearest integral hour) + Correction (table a)
= June the 17th 2001 12h + 10h = June the 17th 22h.

			° ´	Diff.
June 17th	*00h*	*OT,*	δ *= 23 22*	*(+1) N*
	22h	OT,	+ 1	
June 17th	*22h*	*OT,*	$\boldsymbol{\delta}$ ***= 23° 23´ N***	

The latitude of the observer is therefore:

$$\varphi = 90° - ho + \delta = 90° - (68°\ 57{,}17´) + (23°\ 23´) = 44°\ 25{,}8´N$$

B) Solution using Appendix A and the Almanac*:*

The semi diameter of the Sun obtained from the almanac is again 15,7´.

The Greenwich meridian transit of the Sun occurs according to the almanac at 12h 01´ UTC. The meridian transit of the Sun at the observers longitude occurs 56´ 56´´ later (14,2333°/15°) i.e. at 12h 57´ 56´´.

The declination of the Sun at 12h 57´ 56´´ UTC obtained from the almanac is the following:

12h 00´ UTC	*d = 23° 23,3´ (Diff. 0,0´) N*
Increment	*0,0´*
12h 57´ 56´´ UTC	***d = 23° 23,3´ N***

The only difference between the two solutions is therefore 0,3´ (556 m) in latitude.

3530 Find the Sun azimuth at Sunrise/ Sunset

Using Equation (2) from §3440 above one gets:

$$\cos P = \cos Z * \cos B + \sin Z * \sin B * \cos Az$$

Using the definition for the zenith distance during Sunset/Sunrise provided under §3513 above one gets:

$$\cos(90-\delta) = \cos 90{,}8333 * \cos(90-\varphi) + \sin 90{,}8333 * \sin(90-\varphi) * \cos Az$$

Due to the fact cos90,8333° is nearly **"0"** and the sin90,8333° is very close to **"1"**, the influence of those terms to the above equation is negligible, and said equation writes therefore:

$$\sin\delta = 0 + 1 * \cos\varphi * \cos Az$$

Sun azimuth at sunrise / Sunset $\quad Az = \arccos\dfrac{\sin\delta}{\cos\varphi}$

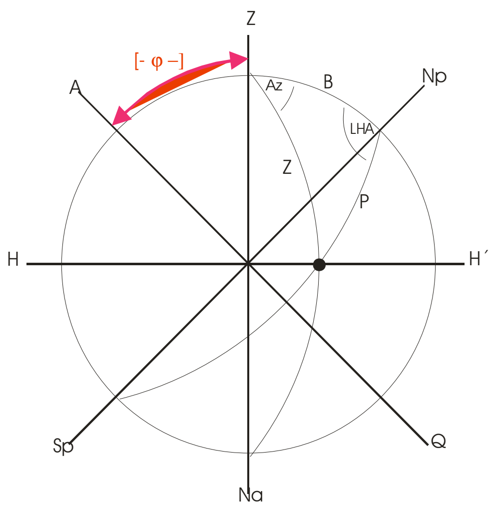


Figure 3530 Sun Azimuth at sunrise

Rules for computation of Z

- When φ and δ are of contrary name δ is treated as a negative quantity.
- When Az is negative, the reference from which Zn starts counting has a name contrary to the name of latitude.
- Zn is counting from its north or south reference to the amount defined by Az to an east or west direction depending on the name of the meridian angle t.

$$\longrightarrow \quad Zn = {}^{N}_{S}\{Az\}^{E}_{W}$$

3540 Find the times of Sunrise/ Sunset as well as for the civil twilight

Applying equation (3) from §3440 above on the astronomical triangle exhibited in figure 3530 one gets:

$$\cos Z = \cos P*\cos B + \sin P*\sin B*\cos LHA$$

This equation provides for given zenith distances of the Sun, its local hour angle prior or after its transit through the observers meridian (LAN).

According to the definition exhibited under §3513 one gets for Sunrise/Sunset the following equation:

$$\cos 90{,}8333° = \cos(90-\delta)*\cos(90-\varphi) + \sin(90-\delta)*\sin(90-\varphi)*\cos LHA$$

$$-0{,}0145 = \sin\delta*\sin\varphi + \cos\delta*\cos\varphi*\cos LHA$$

(1) $$LHA_{Sunrise/Sunset} = \arccos(-tg\delta * tg\varphi - \frac{0{,}0145}{\cos\delta * \cos\varphi})$$

Following the definition provided under §35141 the local hour angle of the sun at the beginning/end of the twilight is calculated as follows:

$$\cos 96° = \cos(90-\delta)*\cos(90-\varphi) + \sin(90-\delta)*\sin(90-\varphi)*\cos LHA$$

$$-0{,}1045 = \sin\delta*\sin\varphi + \cos\delta*\cos\varphi*\cos LHA$$

(2) $$LHA_{Twilight} = \arccos(-tg\delta * tg\varphi - \frac{0{,}1045}{\cos\delta * \cos\varphi})$$

Rules for computation of LHA:

- At Sunrise respectively Sunset LHA is either t_E or t_W.
- When φ and δ are of contrary name δ is treated as a negative quantity.

Example : *Find the times the civil twilight begins and ends, the times of Sunrise and Sunset and the associated azimuths of the Sun for March the 11th 2007 at 37° 3,4´ N latitude and 15° 16,4´ E longitude using the data basis provided in* ***Appendix E.***

Answer: *For Sunrise the meridian transit and the Sunset in Greenwich the following approximate integral GMT hours are selected:*

Sunrise at 06:00 / Meridian transit at 12:OO / Sunset at 18:00

From table (a) of Appendix E it is furthermore obvious that no correction to GMT for the year 2007 is required.

A) Meridian transits of the Sun

Main table, March 11th OT	*E = 02° 26´(+4)*	*02° 26´(+4)*	
Table b for 12h OT	*+2´*	*+2´*	
March 11th for 12h OT corrected	*E = 02° 28´*	*02° 28´*	
Table c for 12h GMT	*355°*		
Table c for 13h GMT		*10°*	
	GHA = 357° 28´	*12° 28´*	

$$\Delta T = \frac{360 - 357,4667}{15} * 60 = 10,1332'$$

Prime meridian transit: 12h 10´ 08´ UTC

Due to the east longitude of the observer the transit trough its meridian occurs 15,2733 / 15=1,0182h earlier i.e. at: ***11h 09´ 02´´ UTC***

Transit (LAN): 12h 09´ 02´´ Local time

B) Beginning of the twilight / Sunrise and Azimuth of the Sun at Sunrise:

Main table, March 11th OT	δ	*03°*	*57´(-24) S*
Table b for 06h OT			*-6´*
March 11th OT corrected	$\boldsymbol{\delta}$	***03°***	***51´ S***

At the beginning of the twilight the LHA of the body can be calculated from the equation (2) provided under §3540 above as follows:

$$LHA = t_E = \arccos[-tg(-3,85) * tg(37,06) - \frac{0,1045}{\cos(-3,85) * \cos(37,06)}] = 94,6159°$$

The distance of the body eastwards of the observer expressed in hours is: 94, 6159 / 15 = 6,3077 hours prior to the local apparent noon.

11h	*09´*	*02´´*	*UTC*
06h	*18´*	*28´´*	*UTC*
04h	*50´*	*34´´*	*UTC*

Twilight begins at: 05h 51´ Local time

At Sunrise the LHA of the body can be calculated from the equation (1) provided under §3540 above as follows:

$$LHA = t_E = \arccos[-tg(-3,85) * tg(37,06) - \frac{0,0145}{\cos(-3,85) * \cos(37,06)}] = 88,1312°$$

The distance of the body eastwards of the observer expressed in hours is: 88,131 / 15 = 5,8754 h prior to the local apparent noon.

11h	*09´*	*02´´*	*UTC*
05h	*52´*	*32´´*	*UTC*
05h	*16´*	*30´´*	*UTC*

Sunrise at: 06h 17´ Local time

The azimuth at Sunrise can be calculated from the equation provided under §3530 above as follows:

$$Az = \arccos\frac{\sin(-3{,}85)}{\cos 37{,}06} = N94{,}8E$$

Sun azimuth at Sunrise: Zn=95°

C) End of the twilight / Sunset and Azimuth of the Sun at Sunset:

Main table, March 11th OT	δ	*03°*	*57´(-24) S*
Table b for 18h OT			*-18´*
March 11th OT corrected	$\boldsymbol{\delta}$	***03°***	***39´ S***

At the end of the twilight the LHA of the body can be calculated from the equation (2) provided under §3540 above as follows:

$$LHA = t_W = \arccos[-tg(-3{,}65) * tg(37{,}06) - \frac{0{,}1045}{\cos(-3{,}65) * \cos(37{,}06)}] = 94{,}7635°$$

The distance of the body eastwards of the observer expressed in hours is: 94, 7635 / 15 = 6,3176 hours prior to the local apparent noon.

11h	*09´*	*02´´*	*UTC*
06h	*19´*	*03´´*	*UTC*
17h	*28´*	*05´´*	*UTC*

Twilight ends at: 18h 28´ Local time

At Sunset the LHA of the body can be calculated from the equation (1) provided under §3540 above as follows:

$$LHA = t_W = \arccos[-tg(-3{,}65) * tg(37{,}06) - \frac{0{,}0145}{\cos(-3{,}65) * \cos(37{,}06)}] = 88{,}2827°$$

The distance of the body eastwards of the observer expressed in hours is: 88,2827 / 15 = 5,8855 h prior to the local apparent noon.

11h	*09´*	*02´´*	*UTC*
05h	*53´*	*08´´*	*UTC*
17h	*02´*	*10´´*	*UTC*

Sunset at: 18h 02´ Local time

The azimuth at Sunset an be calculated from the equation provided under §3530 above as follows:

$$Az = \arccos\frac{\sin(-3{,}65)}{\cos 37{,}06} = N94{,}6W$$

Sun azimuth at Sunset: ***<u>Zn=265°</u>***

3550 Find the longitude at the meridian passage of a body with the double altitude method

For a stationary observer the longitude can be determined by observing the altitude shortly before meridian transit and noting the time when the altitude has returned to exactly the same value after meridian transit. If there has been no change in declination of the body between observations, the mid time represents the moment of meridian transit, at which time the azimuth is 000° or 180°. The GHA (or 360 minus GHA for east longitude) is the longitude of the observer.

Example : *July the 30th 2006 at dead reckoning position 46° 30´ N latitude and 007° 15´ W longitude the lower limp of the Sun around its meridian transit is observed from a height of 2 m using a sextant having zero index failure. The observation data are:*

data are:	*Hs=59°*	*at 12h 01´15´´ UTC (prior meridian transit).*
	Hs=61° 31´	*at meridian transit.*
	Hs=59°	*at 13h 10´21´´ UTC (after meridian transit).*

Find A) the position of the stationary observer and B) the time of Sunset at this position using the data basis provided in ***Appendix E.***

Answer: ***A) Observers position***

From the sight obtained during the meridian transit of the lower limp of the Sun, the altitude of the body during its culmination is calculated as follows:

hs=	*61°*	*31´*	
IC =		*0,0´*	
D =		*-2,52´*	*(DIP=1,779$\sqrt{2}$)*
ha=	*61°*	*28,48´*	
R=		*-0,6*	*(Ref. Appendix A)*
SD=		*+15,7*	
h=	61°	43,58´	(Body elevation)
P=		+0,0	(P=HP*cosh)
ho=	***61°***	***43,6´***	***(Observed altitude)***

Using 12h 00´respectively 13h 00´UTC as the nearest integral hours for the prime meridian transit of the Sun the following information can be extracted from ***Appendix E****:*

OT = GMT (nearest integral hour) + Correction (table a)
= July the 30th 12h/13h + 6h = July the 30th 18h/19h.

Main table, July 30th 00h OT	*E = 03° 23´(+1)*	*03° 23´(+1)*
Table b for 18h/19h OT	*+1´*	*+1´*
July 30th 18h/19h OT	*E = 03° 24´*	*03° 24´*
Table c for 12h 00´ GMT	*355° 00´*	
Table c for 13h 00´GMT		*10° 00´*
	GHA = 358° 24´ /	*13° 24´*

$$\Delta T = \frac{360-358{,}4}{360-358{,}4+13{,}4} * 60 = 6{,}4'$$

Prime meridian Transit: 12h 06´ 24´´ UTC

The meridian transit at longitude of 007° 15´W occurs 29´later than at the prime meridian i.e. at 12h 35,4´ UTC.

For the declination of the Sun 13h GMT will be assumed to be the nearest integral hour to the orbit time.
OT = GMT (nearest integral hour) + Correction (table a)
= July the 30th 2006 13h + 6h = July the 30th 19h.

			° ´	*Diff.*
July 30th	*00h*	*OT,*	δ *= 18 39*	*(-15) N*
	19h	*OT,*	*-12´*	
July 30th	*19h*	*OT,*	δ *= 18° 27´ N*	

The latitude of the observer is therefore:

$$\varphi = 90° - ho + \delta = 90° - (61° \ 43{,}6') + (18° \ 27') = 46° \ 43{,}4' \ N$$

The mid time between the two hs=59° observations is identical to the time of the local apparent noon and amounts to 12,5967 h UTC.

LAN UTC	*12h*	*35´*	*48´´*
Prime meridian UTC	*12h*	*06´*	*24´´*
Delay of the LAN	*00h*	*29´*	*24´´*

Said delay leads to a longitude of the observer:

$$\lambda = 07° \ 21' \ W$$

B) Sunset at the observers position

At Sunset the LHA of the body can be calculated from the equation (1) provided under §3540 above as follows:

$$LHA = t_W = \arccos[-tg(18{,}27) * tg(46{,}7233) - \frac{0{,}0145}{\cos(18{,}27) * \cos(46{,}7233)}] = 111{,}8942°$$

The distance of the body eastwards of the observer expressed in hours is: 111,8942 / 15 =7,4596 h prior to the local apparent noon.

12h	*06´*	*24´´*	*UTC*
07h	*27´*	*35´´*	*UTC*
19h	*33´*	*59´´*	*UTC*

Sunset at: 19h 34´ Local time

PART 4

(Electronic navigation)

Chapter 1

(Electronic charts)

4110 Advantages of electronic charts

Navigators using paper charts are spending far more time taking a fix, working out solutions, and plotting the results, than on making assessments, and the fix only tells him where the vessel was at the time that fix was taken, but not where the ship was some time later when the assessment was made. He is always “behind the vessel” something of little importance at high sees but problematic near shore.

Electronic charts automate the process of integrating real-time positions with the chart display and allow the navigator to continuously assess the position and safety of the vessel. Further, the GPS/DGPS fixes are far more accurate and taken far more often than any navigator ever could. A good piloting team is expected to take and plot a fix every three minutes. An electronic chart system can do it once per second to a standard of accuracy at least an order of magnitude better.

Electronic charts also allow the integration of other operational data, such as ship’s course and speed, depth soundings and radar data into the display. Further, they allow automation of alarm systems to alert the navigator to potentially dangerous situations well in advance of a disaster.

Finally, the navigator has a complete picture of the instantaneous situation of the vessel and all charted dangers in the area. With a radar overlay, the tactical situation with respect to other vessels is clear as well. This chapter will discuss the various types of electronic charts, the requirements for using them, their characteristics, capabilities and limitations.

4120 Terminology

First of all there must be a clear distinction between official and unofficial charts. Official charts are those, and only those, produced by a government hydrographical office (HO). Unofficial charts are produced by a variety of private companies and may or may not meet the same standards used by HO for data accuracy, currency and completeness.

- An **electronic chart system (ECS)** is a commercial electronic chart system not designed to satisfy the regulatory requirements of the IMO Safety of Life at Sea (SOLAS) convention. ECS is an aid to navigation and when used on SOLAS regulated vessels it is to be used in conjunctions with corrected paper charts.

- An **electronic chart display and information system (ECDIS)** is an electronic chart system which satisfies the IMO SOLAS convention carriage requirements for corrected paper charts when used with an ENC or its functional equivalent (e.g. NIMA Digital Nautical Chart.)
- An **electronic chart (EC)** is any digitalized chart intended for display on a computerized navigation system.
- An **electronic navigational chart (ENC)** is an electronic chart issued by a national hydrographical authority designed to satisfy the regulatory requirements for chart carriage.
- **Raster charts** are digitalized pictures of a chart. In other words they are essentially photographs of actual charts. All data is in one layer and one format. The video display simply reproduces the picture from its digitalized data file. With raster data, it is difficult to change individual elements of the chart since they are not separated in the data file. Raster data files tend to be large, since a data point with associated colour and intensity values must be entered for every pixel on the chart. They are pleasing to use and easy to read, as long as there are enough charts of different scales to cover the different zoom levels.
- **Vector** chart data is data that is organized into many separate files or layers. It contains graphic files and programs to produce certain symbols, points, lines, and areas with associated colours, text and other chart elements. The programmer can change individual elements in the file and link elements to additional data. Vector files of a given area are a fraction the size of raster files and at the same time much more versatile. The navigator can selectively display vector data, adjusting the display according to his needs. Vector data supports the computation of precise distances between features and can provide warnings when hazardous situations arise. Also, vector chart file sizes are smaller, which why they are used exclusively on electronic chart plotters.

4130 Legal Aspects of Using Electronic Charts

Requirements for carriage of charts are found in SOLAS Chapter V, which states in part: “All ships shall carry adequate and up-to-date charts necessary for the intended voyage.” As electronic charts have developed and the supporting technology has matured, regulations have been adopted internationally to set standards for what constitutes a “chart” in the electronic sense, and under what conditions such a chart will satisfy the chart carriage requirement.

- By definition, **only an ECDIS can replace a paper chart.** No system which is not an ECDIS relieves the navigator of the responsibility of maintaining a plot on a corrected paper chart.
- An **electronic chart system** should be considered as an aid to navigation, one of many the navigator might have at his disposal to help ensure a safe passage. While possessing revolutionary capabilities, it must be considered as a tool, not an infallible answer to all navigational problems. The rule for the use of electronic charts is the same as for all other aids to navigation: The prudent navigator will never rely completely on any single one.

4140 ECS Standards

Although the IMO has declined to issue guidelines on ECS, the Radio Technical Commission for Maritime Services (RTCM) in the United States developed a voluntary, industry-wide standard for ECS.

Published in December 1994, the RTCM Standard called for ECS to be capable of executing basic navigational functions, providing continuous plots of own ship position, and providing appropriate indicators with respect to information displayed. The RTCM ECS Standard allows the use of either raster or vector data and includes the requirement for simple and reliable updating of information or an indication that the electronic chart information has changed.

In November 2001, RTCM published Version 2.1 of the "RTCM Recommended Standards for Electronic Chart Systems." This updated version is intended to better define requirements applicable to various classes of vessels operating in a variety of areas. Three general classes of vessels are designated:

- Large commercial vessels (ocean-going ships)
- Small commercial vessels (tugs, research vessels etc.)
- Smaller craft (yachts, fishing boats, etc.)

In concept, an ECS meeting the minimum requirements of the RTCM standard should reduce the risk of incidents and improve the efficiency of navigating for many types of vessels.

However, unlike IMO-compliant ECDIS, an ECS is not intended to comply with the up-to-date chart requirements of SOLAS. **As such, an ECS must be considered as a single aid to navigation and should always be used with a corrected chart from a government-authorised hydrographical office.**

PART 4

(Electronic navigation)

Chapter 2

(Satellite navigation)

4210 Introduction

The idea that led to development of the satellite navigation systems dates back to 1957 and the first launch of an artificial satellite into orbit, Russia's Sputnik I. Plotting the signals received from Sputnik at precise intervals, it was noticed that a characteristic Doppler curve emerged.

Since satellites generally follow fixed orbits, it was concluded that this curve could be used to describe the satellite's orbit. Furthermore it has been demonstrated that it was possible to determine all of the orbital parameters for a passing satellite by Doppler observation of a single pass from a single fixed station. Based on this fact it was reasoned in reverse that if the satellite orbit was known, Doppler shift measurements could be used to determine one's position on Earth.

The first successful launching of a prototype system satellite in April 1960 demonstrated the Doppler system's operational feasibility. The **Navy Navigation Satellite System** (**NAVSAT**, also known as **TRANSIT**) was the first operational satellite navigation system. The system's accuracy was better than 0.1 nautical mile anywhere in the world, though its availability was somewhat limited. The transit launch program ended in 1988 and the system was disestablished when the Global Positioning System became operational in 1996.

4220 The US Global Positioning System (GPS)

GPS is a spaced-based radio positioning system which provides suitably equipped users with highly accurate position, velocity and time data.

4221 System Description

The system consists of three major segments: a **space segment**, a **control segment** and a **user segment**.

The **space segment** comprises some 24 satellites. Spacing of the satellites in their orbits is arranged so that at least four satellites are in view to a user at any time, anywhere on the Earth. Each satellite transmits signals on two radio frequencies, superimposed on which are navigation and system data. Included in this data are predicted satellite ephemeris, atmospheric propagation correction data, satellite clock error information, and satellite health data. This segment normally consists of 21 operational satellites with three satellites orbiting as active spares. The satellites orbit at an altitude of 20,200 km, in six separate orbital planes, each plane inclined 55° relative to the equator. The satellites complete an orbit approximately once every 12 hours.

The **control segment** includes a master control station (MCS), a number of monitor stations, and ground antennas located throughout the world.

- The master control station, located in Colorado Springs, Colorado, consists of equipment and facilities required for satellite monitoring, telemetry, tracking, commanding, control, uploading and navigation message generation.
- The monitor stations, located in Hawaii, Colorado Springs, Kwajalein, Diego Garcia, and Ascension Island, passively track the satellites, accumulating ranging data from the satellite signals and relaying them to the MCS.

The MCS processes this information to determine satellite position and signal data accuracy, updates the navigation message of each satellite and relays this information to the ground antennas. The ground antennas then transmit this information to the satellites. The ground antennas, located at Ascension Island, Diego Garcia and Kwajalein are also used for transmitting and receiving satellite control information.

The **user segment** consists of equipment designed to receive and process signals from four or more orbiting satellites either simultaneously or sequentially. The processor in the receiver then converts these signals to navigation information. Since GPS is used in a wide variety of applications, from marine navigation to land surveying, these receivers can vary greatly in function and design.

4222 System Capabilities

GPS provides multiple users with accurate, continuous, worldwide, all-weather, common-grid, three-dimensional positioning and navigation information.

To obtain navigation solution of position (latitude, longitude, and altitude) and time (four unknowns), four satellites must be used. The GPS user measures **pseudo range** and **pseudo range rate** by synchronizing and tracking the navigation signal from each of the four selected satellites.

- **Pseudo range** is the true distance between the satellite and the user plus an offset due to the user's clock bias.
- **Pseudo range rate** is the true slant range rate plus an offset due to the frequency error of the user's clock.

By decoding the ephemeris data and system timing information on each satellite's signal, the user's Receiver/processor can convert the pseudo range and pseudo range rate to three-dimensional position and velocity. Four measurements are necessary to solve for the three unknown components of position (or velocity) and the unknown user time (or frequency) bias.

GPS measures distances between satellites in orbit and a receiver on Earth and computes spheres of position from those distances. The intersections of those spheres of position then determine the receiver's position. The distance measurements described above are done by comparing timing signals generated simultaneously by the satellites' and receiver's internal clocks.

The signal from the satellite arrives at the receiver following a time delay proportional to its distance travelled. Knowing the time required for the signal to reach the receiver from the satellite allows the receiver to calculate the distance from the satellite. The receiver, therefore, must be located on a sphere centred at the satellite with a radius equal to this distance measurement. The intersection of three spheres of position yields two possible points of receiver position. One of these points can be disregarded since it is hundreds of miles from the surface of the Earth. Theoretically, then, only three time measurements are required to obtain a fix from GPS.

In practice, however, a fourth measurement is required to obtain an accurate position from GPS. This is due to receiver clock error. Timing signals travel from the satellite to the receiver at the speed of light; even extremely slight timing errors between the clocks on the satellite and in the receiver will lead to tremendous range errors. The satellite's atomic clock is accurate to 10 to -9 seconds; installing a clock that accurate on a receiver would make the receiver prohibitively expensive. Therefore, receiver clock accuracy is sacrificed, and an additional satellite timing measurement is made. The fix error caused by the inaccuracies in the receiver clock is reduced by simultaneously subtracting a constant timing error from four satellite timing measurements until a pinpoint fix is reached.

The navigation accuracy that can be achieved by any user depends primarily on the variability of the errors in making pseudo range measurements, the instantaneous geometry of the satellites as seen from the user's location on Earth and the presence of **Selective Availability (SA).**

4223 Selective availability

Two levels of navigational accuracy are provided by the GPS: the **Precise Positioning Service (PPS)** and the **Standard Positioning Service (SPS)**.

GPS was designed, first and foremost, by the U.S. Department of Defence as a United States military asset; its extremely accurate positioning capability is an asset access to which the U.S. military may need to limit during time of war to prevent use by enemies. As a consequence, **PPS** provides a more accurate position than does SPS and is available only to authorised users, mainly the U.S. military and authorised allies. whilst on the other hand, **SPS** is available worldwide to anyone possessing a GPS receiver.

For degradation of the nominal accuracy of SPS (approximately 15 meters), the US government uses cryptographic methods introducing specific errors into the satellite signal equivalent to about 100 meters of distance.

4230 Differential GPS (DGPS)

Although the Global Positioning System provides the most accurate positions available to navigators today, it should also be clear that the most accurate positioning information is available to only a small fraction of the using population: U.S. and allied military. For most open ocean navigation applications, the degraded accuracy of the SPS presents no serious hazard to navigation. A mariner seldom if ever needs greater than 100 meter accuracy in the middle of the ocean.

It is a different situation as the mariner approaches shore. Any mariner who has groped his way through a restricted channel in a thick fog will certainly appreciate the fact that even a degraded GPS position is available for them to plot. However, 100 meter accuracy is not sufficient to ensure ship's safety in most piloting situations. The problem then becomes how to obtain the accuracy of the Precise Positioning Service with due regard to the legitimate security concerns of the U.S. military. The answer to this seeming dilemma lies in the concept of Differential GPS (DGPS).

4231 History

Through the early to mid 1980s, a number of agencies developed a solution to the SA "problem". Since the SA signal was changed slowly, the effect of its offset on positioning was relatively fixed – that is, if the offset was "100 meters to the east", that offset would be true over a relatively wide area. This suggested that broadcasting this offset to local GPS receivers could eliminate the effects of SA, resulting in measurements closer to GPS's theoretical performance, around 15 meters. Additionally, another major source of errors in a GPS fix is due to transmission delays in the ionosphere, which could also be measured and corrected for in the broadcast. This offered an improvement to about 5 meters accuracy, more than enough for most civilian needs.

By the mid-1990s it was clear that the SA system was no longer useful in its intended role. DGPS would render it ineffective over the US, precisely where it was considered most needed. Additionally, experience during the Gulf War demonstrated that the widespread use of civilian receivers by U.S. forces meant that SA was thought to harm the U.S. more than if it were turned off. After many years of pressure, it took an executive order by President Bill Clinton to get SA turned off permanently in 2000.

Nevertheless, by this point DGPS had evolved into a system for providing more accuracy than even a non-SA GPS signal could provide on its own. There are several other sources of error that share the same characteristics as SA in that they are the same over large areas and for "reasonable" amounts of time. These include the ionosphere effects mentioned earlier, as well as errors in the satellite position ephemeris data and clock drift on the satellites. Depending on the amount of data being sent in the DGPS correction signal, correcting for these effects can reduce the error significantly, the best implementations offering accuracies of fewer than 10 cm.

In addition to continued deployments of the United States Coast Guard (USCG) and the Federal Aviation Administration (FAA), sponsored systems, a number of vendors have created commercial DGPS services, selling their signal (or receivers for it) to users who require better accuracy than the nominal 15 meters GPS offers. For suitably equipped users, DGPS results in positions better than or at least as accurate as those obtainable by the PPS.

4232 Operation

Differential GPS is a system in which a reference station at an accurately surveyed position utilises GPS signals to calculate the distance to each satellite, timing errors, Pseudo Range and Range Rate Corrections and then broadcasts correction information on long wave radio frequencies between 285 kHz and 325 kHz to account for these errors. These frequencies are commonly used for marine radio, and are broadcast near major waterways and harbours. The extremely high altitude of the GPS satellites means that, as long as the DGPS receiver is within 100-200 km of the user's receiver, the user's receiver is close enough to take advantage of any DGPS correction signal.

4233 Drawbacks and limitations

For all its benefits, DGPS is not without drawbacks and critical limitations.One of the most important effects limiting the accuracy of DGPS is the so called "Spatial decorrelation". This effect compromises the accuracy of the position calculated by the DGPS receiver drastically if the distance between the DGPS reference station and the Receiver is in excess of 100 nautical miles. With increasing distance of the DGPS receiver from the reference station it is obvious,

- that the satellite signals used by the reference station and the receiver pass through different parts of the atmosphere and are therefore experiencing different delays and
- that the receiver may use different satellites then those for which the reference station broadcasts correction data.

4240 Wide Area Augmentation System (WAAS)

WAAS is primarily an air navigation aid developed by the Federal Aviation Administration to augment the **Global Positioning System** (GPS), with the goal of improving its accuracy, integrity, and availability. Essentially, WAAS is intended to enable aircraft to rely on GPS for all phases of flight, including precision approaches to any airport within its coverage area.

WAAS uses a network of ground-based reference stations, in North America and Hawaii, to measure small variations in the GPS satellites' signals in the western hemisphere. Measurements from the reference stations are routed to master stations, which queue the received **Deviation Correction** (DC) and send the correction messages to geostationary WAAS satellites in a timely manner (every 5 seconds or better). Those satellites broadcast the correction messages back to Earth, where WAAS-enabled GPS receivers use the corrections while computing their positions to improve accuracy.

This type of system is called a **Satellite Based Augmentation System (SBAS)**. Europe and Asia are developing their own SBAS, the Indian **GPS Aided Geo Augmented Navigation (GAGAN)**, the **European Geostationary Navigation Overlay Service (EGNOS)** and the Japanese **Multi-functional Satellite Augmentation System (MSAS)**. All four systems operate under the same philosophy and are compatible to each other.

4241 System description

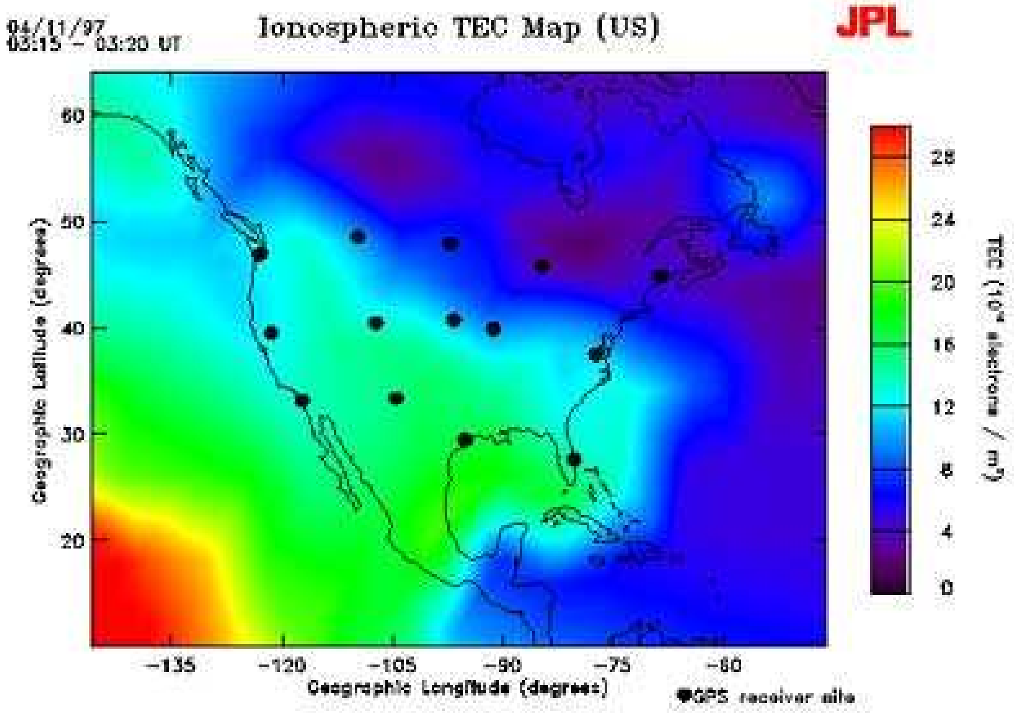
As with GPS in general, WAAS is composed of three main segments; the **Ground segment**, the **Space segment**, and the **User segment**.

The **Ground Segment** is composed of multiple **Wide-area Reference Stations (WRS).** These precisely surveyed ground stations monitor and collect information on the GPS signals, and then send their data to the three **Wide-area Master Stations (WMS)** using a terrestrial communications network.

The reference stations also monitor the signal from the WAAS geostationary satellites, providing integrity information regarding them as well. As of October 2007 there are 38 WRS, twenty in the contiguous United States, seven in Alaska, one in Hawaii, one in Puerto Rico, five in Mexico, and four in Canada.

Using the data from the WRS sites, the WMS generate two different sets of corrections: fast and slow. The fast corrections are for errors which are changing rapidly and primarily concern the GPS satellites' instantaneous positions and clock errors. These corrections are considered user position independent, which means they can be applied instantly by any receiver in the WAAS broadcast footprint. The slow corrections include long-term ephemeric and clock error estimates, as well as ionospheric delay information.

From the data collected by the WRS, WAAS calculates the Total Electron Content **(TEC)** of the area covered by the RMS and supplies the appropriate ionospheric delay corrections for a number of points (organized in a grid pattern) across the WAAS service area.



Once these corrections are generated, the WMS then send them to the two pairs of **Ground Uplink Stations (GUS)** which transmit them to the satellites in the Space segment for broadcast to the User segment.

The **space segment** consists of multiple geosynchronous communication satellites which broadcast the correction messages generated by the Wide-area Master Stations for reception by the User segment. The satellites also broadcast the same type of range information as normal GPS satellites, effectively increasing the number of satellites available for a position fix. All GPS signal sources are identified by a code division multiple access modulation (CDMA) system which places a unique sub-carrier modulation on the course acquisition carrier of each signal. These modulation patterns are known as **pseudo-random noise (PRN)** codes

With the end of the Inmarsat lease approaching, two new satellites (Galaxy 15 and Anik F1R) were launched in late 2005. Since September 23, 2008, the ranging data that Galaxy 15 and Anik F1R transmit have been flagged as "Precision Approach."

Satellite	NMEA / PRN	Location
Galaxy 15	NMEA 48 / PRN 135	133°W
Anik F1R	NMEA 51 / PRN 138	107,3°W

The **User segment** is the GPS and WAAS receiver, which uses the information broadcast from each GPS satellite to determine its location and the current time, and receives the WAAS corrections from the Space segment.

The two types of correction messages received (fast and slow) are used in different ways. The GPS receiver can immediately apply the fast type of correction data, which includes the corrected satellite position and clock data, and determines its current location using normal GPS calculations. Once an approximate position fix is obtained the receiver begins to use the slow corrections to improve its accuracy. Among the slow correction data is the ionospheric delay. As the GPS signal travels from the satellite to the receiver, it passes through the ionosphere. The receiver calculates the location where the signal pierced the ionosphere and, if it has received an ionospheric delay value for that location, corrects for the error the ionosphere created.

While the slow data can be updated every minute if necessary, ephemeris errors and ionosphere errors do not change this frequently, so they are only updated every two minutes and are considered valid for up to six minutes.

4242 Accuracy

The WAAS specification requires it to provide a position accuracy of 7.6 meters or better (for both lateral and vertical measurements), at least 95% of the time. Actual performance measurements of system at specific locations have shown it typically provides better than 1.0 meters laterally and 1.5 meters vertically throughout most of the contiguous United States and large parts of Canada and Alaska. With these results, WAAS is capable of achieving the required **Category I precision approach** accuracy of 16 m laterally and 4.0 m vertically.

4250 Global Navigation Satellite System (GLONASS)

The GLONASS under the control of the Russian military, has been in use since 1993 and is based on the same principles as GPS. The space segment consists of 24 satellites in three orbital planes, the planes separated by 120 degrees and the individual satellites by 45 degrees.

The orbits are inclined to the equator at an angle of 64.8 degrees and the orbital period is about 11hours, 15minutes at an altitude of 19,1 km (10,313 nm). The designed system fix accuracy for civilian use is 100 meters horizontal (95%), 150 meters vertical, and 15 cm/sec. in velocity. Military codes provide accuracies of some 10-20 meters horizontal.

The ground segment of GLONASS lies entirely within the former Soviet Union. The user segment consists of various types of receivers that provide position, time, and velocity information.

4260 The Galileo System

In early 2002 the European Union (EU) decided to fund the development of its new Galileo satellite navigation system which shall be compatible with the U.S. GPS. A great deal of preliminary scientific work has already been accomplished, and full scale development is under way.

In contrast to GPS and GLONASS, Galileo will be under civilian control and dedicated primarily to civilian use. Plans call for the Galileo constellation to consist of 30 satellites (27 usable and three spares) in three orbital planes, each inclined 56 degrees to the equator. The orbits are at an altitude of 23,616 km (about 12,750 Nm).

Galileo will be designed to serve higher latitudes than GPS, an additional factor in the EU decision, based on Scandinavian participation. Galileo will also provide an important feature for civilian use that GPS does not: integrity monitoring. Currently, a civilian GPS user receives no indication that his unit is not receiving proper satellite signals, there being no provision for such notification in the code. However, Galileo will provide such a signal, alerting the user that the system is operating improperly.

The issue of compatibility with GPS is being addressed during ongoing development. Frequency sharing with GPS is under discussion, and it is reasonable to assume that a high degree of compatibility will exist when Galileo is operational. Manufacturers will undoubtedly offer a variety of systems which exploit the best technologies of both GPS and Galileo.

The benefit of Galileo for the navigator is that there will be two separate satellite navigation systems to rely on, providing not only redundancy, but also an increased degree of accuracy (for systems that can integrate both systems' signals). Galileo should be first available in 2006, and the full constellation is scheduled to be up by 2010.

4261 European Geostationary Navigation Overlay System (EGNOS)

EGNOS is like WAAS a Satellite Based Augmentation System **(SBAS)**, and is compatible to WAAS. Since 2005 EGNOS is under Test using a specific **EGNOS Satellite Test Bed (ESTB)**.

In the final configuration the **Ground Segment** will composed of 34 **Ranging and Integrity Monitor Stations (RIMS).** These precisely surveyed ground stations monitor and collect information on the GPS signals, and then send their data to four **Mission Control Centers (MCC)** located in Langen (Frankfurt/Germany), Torrejon (Madrid/Spain), Ciampino

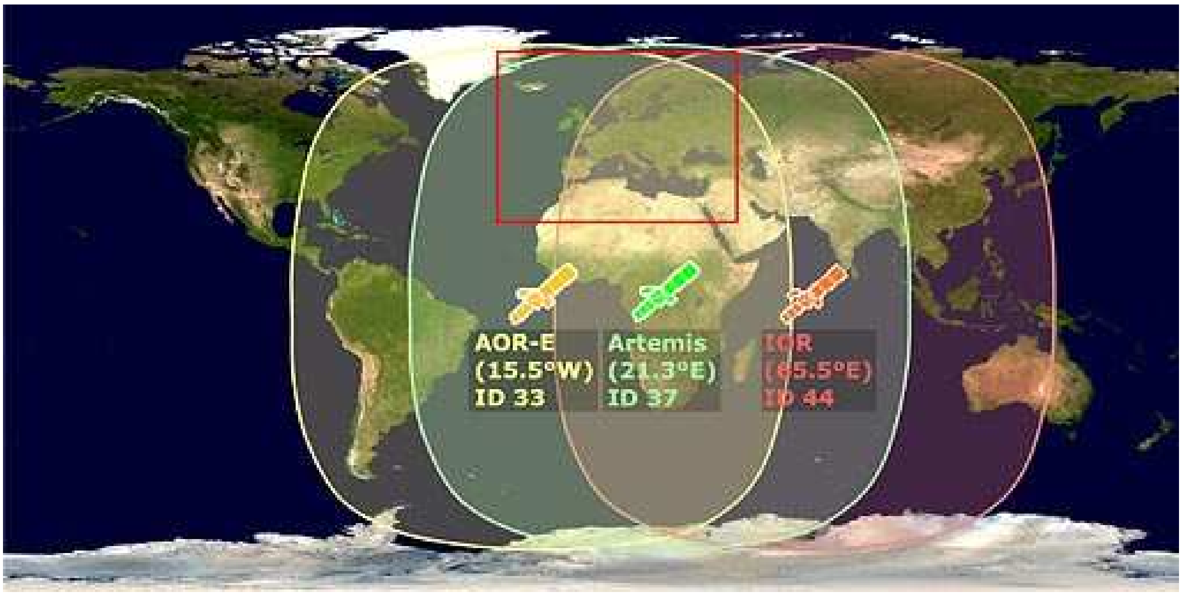
(Rom/Italy) and Swanwick London/UK) using a terrestrial communications network Using the data provided by the RIMS the MCC calculate:

- Long term errors in the Satellite position
- Short and long term Satellite clock errors
- Ionospheric correction grids
- Integrity information

With the integrity information, the user will be warned within 6 seconds after appearance of a problem that the quality of the signal he is using is doubtful.

In the final configuration the **Space Segment** will rely on the following three geostationary satellites (two Inmarsat plus Artemis):

Satellite	ID / PRN	Location
INMARSAT 3 F2 (AOR-E)	ID 33 / PRN 120	15,5°W
Artemis	ID 37 / PRN 124	21,3°E
INMARSAT 3 F1 (IOR)	ID 44 / PRN 131	65,5°E



Position and coverage area of the EGNOS satellites

PART 4

(Electronic navigation)

Chapter 3

(Radar navigation)

4310 Introduction

The word radar is an acronym derived from the phrase **RA**dio **D**etection **A**nd **R**anging and applies to electronic equipment designed for detecting and tracking objects (targets) at considerable distances.

Radar determines distance to an object by measuring the time required for a radio signal to travel from a transmitter to an object and return. Since most radars use directional antennae, they can also determine an object's bearing. However, radar's bearing measurement will be less accurate than its distance measurement. Typically, a radar bearing is accurate to within about 5° of true bearing. Understanding this concept is crucial to ensuring the optimal employment of the radar for safe navigation.

4311 Signal Characteristics

Signals are generated by a timing circuit so that energy leaves the antenna in very short pulses. When transmitting, the antenna is connected to the transmitter but not the receiver. As soon as the pulse leaves, an electronic switch disconnects the antenna from the transmitter and connects it to the receiver. Another pulse is not transmitted until after the preceding one has had time to travel to the most distant target within range and return. The returned pulses are displayed on an indicator screen.

Since the interval between pulses is long compared with the length of a pulse, strong signals can be provided with low average power.

4312 The Display

On conventional Circular Cathode Ray Tube **(CRT)** displays, the display sweep starts at its centre and moves outward along a radial line rotating in synchronisation with the antenna. Detection is indicated by a brightening of the display screen at the bearing and range of the return. Because of a luminescent tube face coating, the glow continues after the trace rotates past the target. The target's actual range is proportional to its echo's distance from the scope's centre. A moveable cursor helps to measure ranges and bearings. In the "heading-upward" presentation, which indicates relative bearings, the top of the scope represents the direction of the ship's head.

The raster radar also employs a cathode ray tube. In this basic radar system, the type of display used is the Plan Position Indicator **(PPI)**, which is essentially a polar diagram, with the transmitting ship's position at the centre. However, the raster radar does not produce its picture from a circular sweep. It utilizes a liner scan in which the picture is "drawn" line by line, horizontally across the screen. As the sweep moves across the screen, the electron beam from the CRT illuminates the pixels on the screen. A pixel is the smallest area of phosphorus that can be excited to form a picture element. In order to produce a sufficiently high resolution, some raster radars require over 1 million pixels per screen combined with an update rate of 60 scans per second. Completing the processing for such a large number of pixel elements requires sophisticated, expensive circuitry. One way to lower cost is to slow down the required processing speed. This speed can be lowered to approximately 30 frames per second before the picture develops a noticeable flicker.

4320 The Radar Beam

The pulses of r-f energy emitted from the feed horn at the focal point of a reflector or emitted and radiated directly from the slots of a slotted waveguide antenna would, for the most part, form a single lobe-shaped pattern of radiation if emitted in free space. Figure 4320 below illustrates this free space radiation pattern, including the undesirable minor lobes or SIDE LOBES associated with practical antenna design. Because of the large differences in the various dimensions of the radiation pattern, figure 4320 is necessarily distorted.

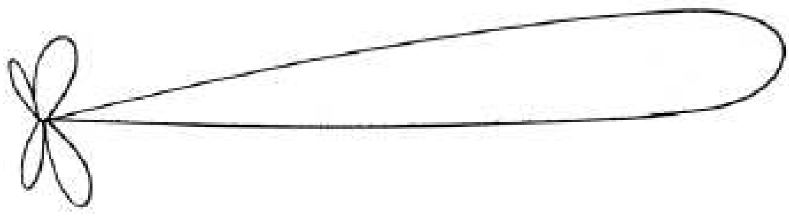


Figure 4320 Free space radiation pattern

Although the radiated energy is concentrated or focused into a relatively narrow main beam by the antenna, similar to a beam of light from a flashlight, there is no clearly defined envelope of the energy radiated. While the energy is concentrated along the axis of the beam, its strength decreases with distance along the axis. The strength of the energy decreases rapidly in directions away from the beam axis.

The power in watts at points in the beam is inversely proportional to the square of the distance. Therefore, the power at 3 miles is only 1/9th of the power at 1 mile in a given direction. The field intensity in volts at points in the beam is inversely proportional to the distance. Therefore, the voltage at 2 miles is only one-half the voltage at 1 mile in a given direction. With the rapid decrease in the amount of radiated energy in directions away from the axis and in conjunction with the rapid decreases of this energy with distance, it follows that practical limits of power or voltage may be used to define the dimensions of the radar beam or to establish its envelope of useful energy.

4321 Beam Width

The three-dimensional radar beam is normally defined by its horizontal and vertical beam widths. Beam width is the angular width of a radar beam between points within which the field strength or power is greater than arbitrarily selected lower limits of field strength or power.

The most frequently used convention to define beam width is the **half power ratio** definition. This convention defines beam width as the angular width between points at which the field strength drops to -3 dB of its maximum value.

The radiation diagram illustrated in Figure 4321 below depicts relative values of power in the same plane existing at the same distances from the antenna or the origin of the radar beam. Maximum power is in the direction of the axis of the beam. Power values diminish rapidly in directions away from the axis. The beam width is therefore the angle between the half-power points.

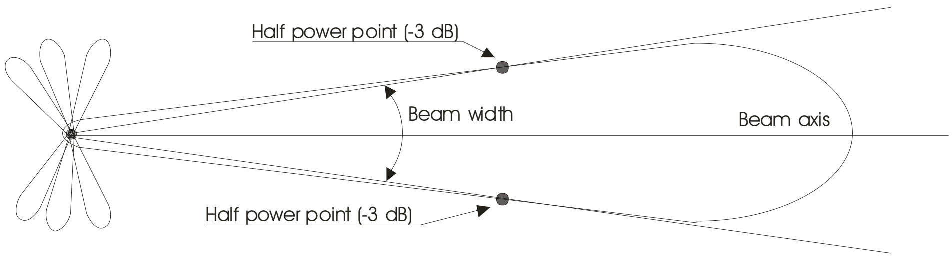


Figure 4321 Radiation diagram

For a given amount of transmitted power, the main lobe of the radar beam extends to a greater distance at a given power level with greater concentration of power in narrower beam widths. To increase maximum detection range capabilities, the energy is concentrated into as narrow a beam as is feasible. Because of practical considerations related to target detection and discrimination, only the horizontal beam width is quite narrow, typical values being between about 0.65° to 2.0°. The vertical beam width is relatively broad, typical values being between about 15° to 30°.

The beam width depends upon the frequency or wavelength of the transmitted energy, antenna design and the dimensions of the antenna. For a given antenna size (antenna aperture), narrower beam widths are obtained when using shorter wavelengths. For a given wavelength, narrower beam widths are obtained when using larger antennas.

4322 Effect of sea surface on radar beam

With radar waves being propagated in the vicinity of the surface of the sea, the main lobe of the radar beam, as a whole, is composed of a number of separate lobes as opposed to the single lobe-shaped pattern of radiation as emitted in free space. This phenomenon is the result of interference between radar waves directly transmitted and those waves which are reflected from the surface of the sea.
The vertical beam widths of navigational radars are such that during normal transmission radar waves will strike the surface of the sea at points from near the antenna (depending upon antenna height and vertical beam width) to the radar horizon. The indirect waves (see Figure

4322) reflected from the surface of the sea may, on rejoining the direct waves, either reinforce or cancel the direct waves depending upon whether they are in phase or out of phase with the direct waves, respectively. Along directions away from the antenna, the direct and indirect waves will gradually come into and pass out of phase, producing lobes of useful radiation separated by regions within which, for practical purposes, there is no useful radiation.

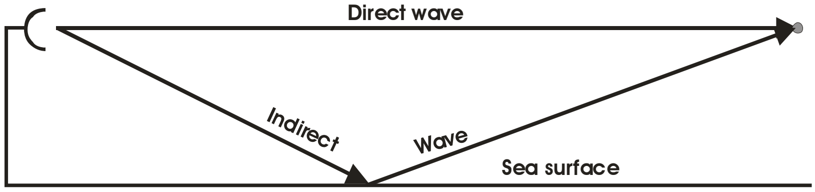


Figure 4322 Direct and indirect Waves

It is therefore obvious that if r-f energy is to be reflected from a target, the target must extend somewhat above the radar horizon, the amount of extension being dependent upon the reflecting properties of the target.

4330 Weather factors affecting the radar horizon

The usual effects of weather are to reduce the ranges at which targets can be detected and to produce unwanted echoes on the radarscope which may obscure the returns from important targets or from targets which may be dangerous to one's ship. The reduction of intensity of the wave experienced along its path is known as attenuation. Attenuation is caused by the absorption and scattering of energy by the various forms of precipitation. The amount of attenuation caused by each of the various factors depends to a substantial degree on the radar wavelength. It causes a decrease in echo strength. Attenuation is greater at the higher frequencies or shorter wavelengths.

The amount of attenuation caused by weather factors is dependent upon the amount of water, liquid or frozen, present in a unit volume of air and upon the temperature. Therefore, as one would expect, the affects can differ widely. The further the radar wave and returning echo must travel through this medium then the greater will be the attenuation and subsequent decrease in detection range. This is the case whether the target is in or outside the precipitation. A certain amount of attenuation takes place even when radar waves travel through a clear atmosphere. The affect will not be noticeable to the radar observer. The effect of precipitation starts to become of practical significance at wavelengths shorter than 10cm. In any given set of precipitation conditions, the (S-band) or 10cm will suffer less attenuation than the (X-band) or 3cm.

Rain: In the case of rain the particles which affect the scattering and attenuation take the form of water droplets. It is possible to relate the amount of attenuation to the rate of precipitation. If the size of the droplet is an appreciable proportion of the 3cm wavelength, strong clutter echoes will be produced and there will be serious loss of energy due to scattering and attenuation. If the target is within the area of rainfall, any echoes from raindrops will further decrease its detection range. Weaker target responses, as from small vessels and buoys, will be undetectable if their echoes are not stronger than that of the rain. A very heavy rainstorm, like those sometimes encountered in the tropics, can obliterate most of the (X-band) radar picture. Continuous rainfall over a large area will make the centre part of the screen brighter than the rest and the rain clutter, moving along with the ship, looks similar to sea clutter. It can be clearly seen on long range scales. This is due to a gradual decrease in returning power as the pulse penetrates further into the rain area.

Fog: In most cases fog does not actually produce echoes on the radar display, but a very dense fogbank which arises in Polar Regions may produce a significant reduction in detection range. A vessel encountering areas known for industrial pollution in the form of smog may find a somewhat higher degree of attenuation than sea fog.

Clouds: The water droplets which form clouds are too small to produce a detectable response at the 3cm wavelength. If there is precipitation in the cloud then the operator can expect a detectable echo.

Hail: With respect to water, hail which is essentially frozen rain reflects radar energy less effectively than water. Therefore, in general the clutter and attenuation from hail are likely to prove less detectable than that from rain.

Snow: Similar to the effects of hail, the overall effect of clutter on the picture is less than that due to rain. The strength of echoes from snow depends upon the size of the snowflake and the rate of precipitation. Falling snow will only be observed on the displays of 3cm except during heavy snowfall where attenuation can be observed on a 10cm set.

Dust: There is a general reduction in radar detection in the presence of dust and sandstorms. On the basis of particle size, detectable responses are extremely unlikely and the operator can expect a low level of attenuation.

Unusual Conditions: Similar to the propagation of light waves, radar waves going through the Earth’s atmosphere are subject to refraction and normally bend slightly with the curvature of the Earth. Certain atmospheric conditions will produce a modification of this normal refraction.

4340 Factors affecting detection, display and measurement of range

The factors influencing the maximum and minimum range, the range accuracy and resolution are discussed below.

4341 Factors affecting maximum range

Frequency: The higher the frequency of a radar wave, the greater is the attenuation, regardless of weather. Lower radar frequencies (longer wavelengths) have, therefore, been generally superior for longer detection ranges.

Peak Power: The peak power of radar is its useful power. Range capabilities of the radar increase with peak power. Doubling the peak power increases the range capabilities by about 25 percent.

Pulse Length: The longer the pulse length, the greater is the range capability of the radar because of the greater amount of energy transmitted.

Pulse Repetition Rate: The pulse repetition rate **(PRR)** determines the maximum measurable range of the radar. Ample time must be allowed between pulses for an echo to return from any target located within the maximum workable range of the system. Otherwise, echoes returning from the more distant targets are blocked by succeeding transmitted pulses. This necessary time interval determines the highest PRR that can be used. The PRR must be high enough, however, that sufficient pulses hit the target and enough echoes are returned to the radar. The maximum measurable range can be determined approximately by dividing 81.000 by the PRR.

Beam Width: The more concentrated the beam, the greater is the detection range of the radar.

Target Characteristics: Targets that are large can be seen on the scope at greater ranges, provided line-of-sight exists between the radar antenna and the target. Conducting materials (a ship’s steel hull, for example) return relatively strong echoes while non conducting materials (a wood hull of a fishing boat, for example) return much weaker echoes.

Receiver Sensitivity: The more sensitive receivers provide greater detection ranges but are more subject to jamming.

Antenna Rotation Rate: The more slowly the antenna rotates, the greater is the detection range of the radar. For a radar set having a PRR of 1.000 pulses per second, a horizontal beam width of 2°, and an antenna rotation rate of 6 RPM (1 revolution in 10 seconds or 36 scanning degrees per second), there is 1 pulse transmitted each

0,036° of rotation. There are 56 pulses transmitted during the time required for the antenna to rotate through its beam width.

Beam Width / Degrees per Pulse = 2° / 0,036° = 56 Pulses

With an antenna rotation rate of 15 RPM (1 revolution in 4 seconds or 90 scanning degrees per second), there is only 1 pulse transmitted each 0,090° of rotation. There are only 22 pulses transmitted during the time required for the antenna to rotate through its beam width.

Beam Width / Degrees per Pulse = 2° / 0,09° = 22 Pulses

From the foregoing it is apparent that at the higher antenna rotation rates, the maximum ranges at which targets, particularly small targets, may be detected are reduced.

4342 Factors affecting minimum range

Pulse Length: The minimum range capability of a radar is determined primarily by the pulse length. It is equal to half the pulse length of the radar.

Sea Return: Sea return or echoes received from waves may clutter the indicator within and beyond the minimum range established by the pulse length and recovery time.

Side-Lobe Echoes: Targets detected by the side-lobes of the antenna beam pattern are called side-lobe echoes. When operating near land or large targets, side-lobe echoes may clutter the indicator and prevent detection of close targets, without regard to the direction in which the antenna is trained.

Vertical Beam Width: Small surface targets may escape the lower edge of the vertical beam when close.

4343 Factors affecting range accuracy

The range accuracy of radar depends upon the exactness with which the time interval between the instants of transmitting a pulse and receiving the echo can be measured.

Fixed Error: A fixed range error is caused by the starting of the sweep on the indicator before the r-f energy leaves the antenna. The zero reference for all range measurements must be the leading edge of the transmitted pulse as it appears on the indicator.

Line Voltage: Accuracy of range measurement depends on the constancy of the line voltage supplied to the radar equipment. If supply voltage varies from its nominal value, ranges indicated on the radar may be unreliable.

Frequency Drift: Errors in ranging also can be caused by slight variations in the frequency of the oscillator used to divide the sweep (time base) into equal range intervals.

Calibration: Radar indicators usually have a Variable Range Marker **(VRM)** or adjustable range ring which is the normal means for range measurements. With the VRM calibrated with respect to the fixed range rings within a tolerance of 1 percent of the maximum range of the scale in use, ranges as measured by the VRM may be in error by as much as 2,5 percent of the maximum range of the scale in use. With the indicator set on the 8-mile range scale, the error in a range as measured by the VRM may be in error by as much as 0,2 nautical mile.

Radarscope Interpretation: Relatively large range errors can result from incorrect interpretation of a landmass image on the PPI. The difficulty of radarscope interpretation can be reduced through more extensive use of height contours on charts. For reliable interpretation it is essential that the radar operating controls be adjusted properly. If the receiver gain is too low, features at or near the shoreline, which would reflect echoes at a higher gain setting, will not appear as part of the landmass image. If the receiver gain is too high, the landmass image on the PPI will “bloom”. With blooming the shoreline will appear closer than it actually is. A fine focus adjustment is necessary to obtain a sharp landmass image on the PPI. Because of the various factors introducing errors in radar range measurements, one should not expect the accuracy of navigational radar to be better than + or - 50 m under the best conditions.

4344 Factors affecting range resolution

Range resolution is a measure of the capability of a radar to display as separate pips the echoes received from two targets which are on the same bearing and are close together. The principal factors that affect the range resolution of a radar are the length of the transmitted pulse, receiver gain, CRT spot size, and the range scale. A high degree of range resolution requires a short pulse, low receiver gain, and a short range scale.

Pulse Length: Since the radio frequency energy travels at a speed of 300 million meters per second, the distance the energy travels in 1 microsecond is approximately 300 meters. Because the energy must make a round trip, the target cannot be closer than 150 meters if its echo is to be seen on the screen while using a pulse length of 1 microsecond. For the same reason two targets on the same bearing, close together, cannot be seen as two distinct pips on the PPI unless they are separated by a distance greater than one-half the pulse length (150 meters per microsecond of pulse length). If a 1-microsecond pulse is sent toward two objects on the same bearing, separated by 150 meters, the leading edge of the echo from the distant target coincides in space with the trailing edge of the echo from the near target. As a result the echoes from the two objects blend into a single pip, and range can be measured only to the nearest object. The reason for this blending is illustrated in figure 4344a below.

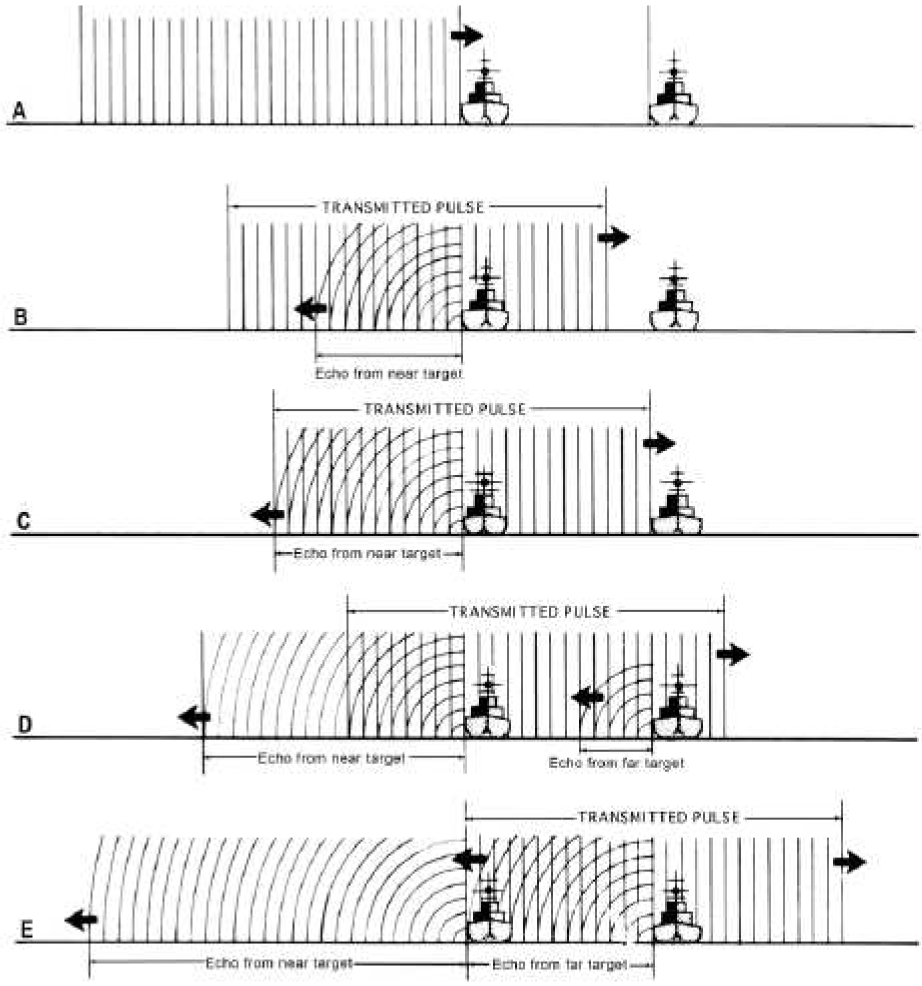


Figure 4344a Pulse length and range resolution

In part A of figure 4344a above, the transmitted pulse is just striking the near target. Part B shows energy being reflected from the near target, while the leading edge of the transmitted pulse continues toward the far target. In part C, 1/2 microsecond later, the transmitted pulse is just striking the far target; the echo from the near target has travelled 150 meters back toward the antenna. The reflection process at the near target is only half completed. In part D echoes are travelling back toward the antenna from both targets. In part E reflection is completed at the near target. At this time the leading edge of the echo from the far target coincides with the trailing edge of the first echo. When the echoes reach the antenna, energy is delivered to the set during a period of 2 microseconds so that a single pip appears on the PPI. If a radar has a pulse length of 1 microsecond duration, the targets would have to be separated by more than 150 meters before they would appear as two pips on the PPI.

Receiver Gain: Range resolution can be improved by proper adjustment of the receiver gain control. As illustrated in figure 4344b below, the echoes from two targets on the same bearing may appear as a single pip on the PPI if the receiver gain setting is too high. With reduction in the receiver gain setting, the echoes may appear as separate pips on the PPI.

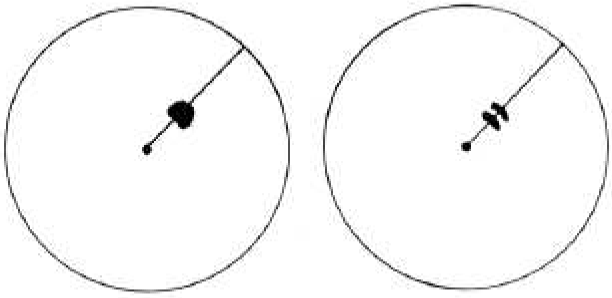


Figure 4344b Receiver gain and range resolution

4350 Factors affecting detection, display and measurement of bearing

The factors influencing bearing accuracy and resolution are discussed below.

4351 Factors affecting bearing accuracy

Horizontal beam width: Bearing measurements can be made more accurately with the narrower horizontal beam widths. Several targets close together may return echoes which produce pips on the PPI which merge, thus preventing accurate determination of the bearing of a single target within the group. The effective beam width can be reduced through lowering the receiver gain setting. In reducing the sensitivity of the receiver, the maximum detection range is reduced, but the narrower effective beam width provides better bearing accuracy.

Target Size: For a specific beam width, bearing measurements of small targets are more accurate than large targets because the centres of the smaller pips of the small targets can be identified more accurately.

Sweep Centring Error: If the origin of the sweep is not accurately centred on the PPI, bearing measurements will be in error. Greater bearing errors are incurred when the pip is near the centre of the PPI than when the pip is near the edge of the PPI. Since there is normally some centring error, more accurate bearing measurements can be made by changing the range scale to shift the pip position away from the centre of the PPI.

4352 Factors affecting bearing resolution

Bearing resolution is a measure of the capability of a radar to display as separate pips the echoes received from two targets which are at the same range and are close together.

The principal factor that affects the bearing resolution of a radar is the horizontal beam width.

Horizontal beam width: As the radar beam is rotated, the painting of a pip on the PPI begins as soon as the leading edge of the radar beam strikes the target. The painting of the pip is continued until the trailing edge of the beam is rotated beyond the target. Therefore, the pip is distorted angularly by an amount equal to the effective horizontal beam width. As illustrated in figure 4352 below, in which a horizontal beam width of 10° is used for graphical clarity only, the actual bearing of a small target having good reflecting properties is 090°, but the pip as painted on the PPI extends from 095° to 085°. The left 5° and the right 5° are painted while the antenna is not pointed directly towards the target. The bearing must be read at the centre of the pip.

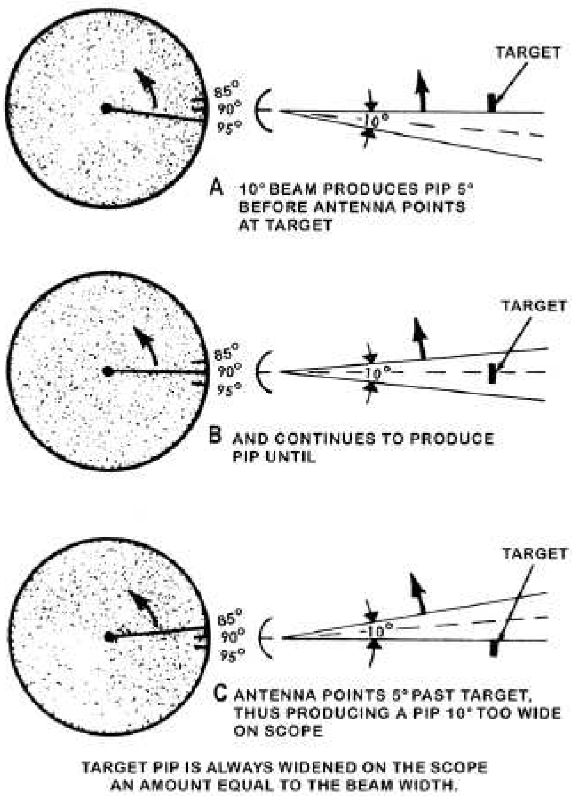


Figure 4352 Angular distortion

4360 Manoeuvring Board

The manoeuvring Board is a diagram which can be used in the solution of relative motion problems. The chart as illustrated in figure 4360 consists primarily of a polar diagram having equally spaced radials and concentric circles. The radials are printed as dotted lines at 10° intervals. The 10 concentric cycles are also dotted except for the inner and the outer complete circle.

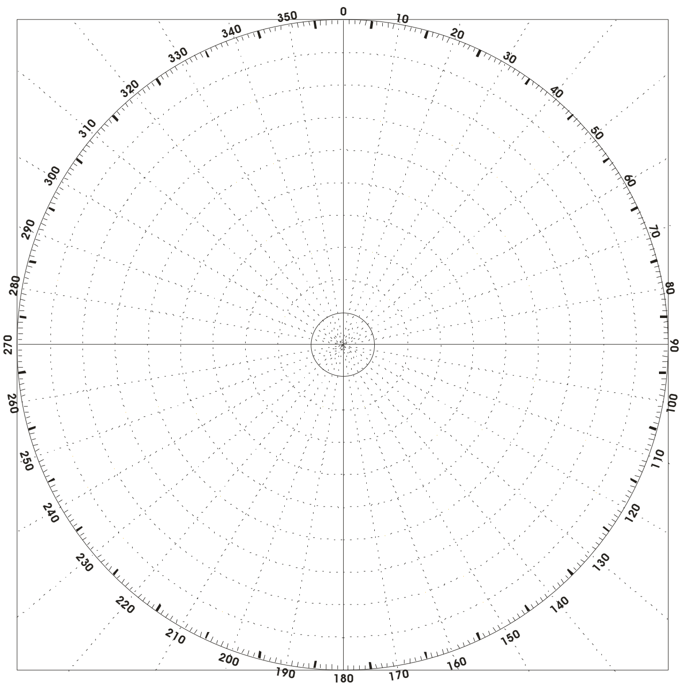


Fig. 4360 Manoeuvring Board

In plotting the ranges and bearings of radar targets on the Manoeuvring Board, the radar observer generally must select an optimum distance scale. For radar targets at distances between 10 and 20 miles, the 2:1 scale is the best selection. The objective is to provide as much separation between individual plots as is possible for both clarity and accuracy of plotting. While generally either the 1:1 or 2:1 scale is suitable for plotting the relative positions of the radar contacts in collision avoidance applications when the ranges are measured in miles, the radar observer also must select a suitable scale for the graphical construction of the vector triangles when the sides of these triangles are scaled in knots.

To avoid confusion between scales being used for distance and speed in Knots, the radar observer should make a notation on the Manoeuvring Board as to which scale is being used for distance and which scale is being used for speed in knots.

4361 Radar Plotting Symbols

In order to be able to maintain a clear separation of data of the own ship from those of a contact on the manoeuvring board the following abbreviation shall be used.

Relative Plot		Vector Triangle	
Symbol	**Meaning**	**Symbol**	**Meaning**
R	Own Ship.	e	The origin of any ship's true (course-speed) vector fixed with respect to the earth.
M	Other Ship.	r	The end of own ship's true (course-speed) vector, *er*; the origin of the relative (DRM-SRM) vector, *rm*.
M1	First plotted position of other ship.	*r*1, *r*2	The ends of alternative true (course-speed) vectors for own ship.
M2, M3	Later positions of other ship.	er	Own ship's true (course-speed) vector.
Mx	Position of other ship on RML at planned time of evasive action; point of execution.	m	The end of other ship's true (course-speed) vector, *em*; the end of the relative (DRM-SRM) vector, r*m.*
NRML	New relative movement line.	em	Other ship's true (course-speed) vector.
RML	Relative movement line.	rm	The relative (DRM-SRM) vector; always in the direction of M1/ M2/ M3........
DRM	Direction of relative movement; always in the direction of M1/ M2/ M3........		
SRM	Speed of relative movement.		
MRM	Miles of relative movement; relative distance travelled.		
CPA	Closed point of approach.		

4362 Examples

43621 Closest point of approach

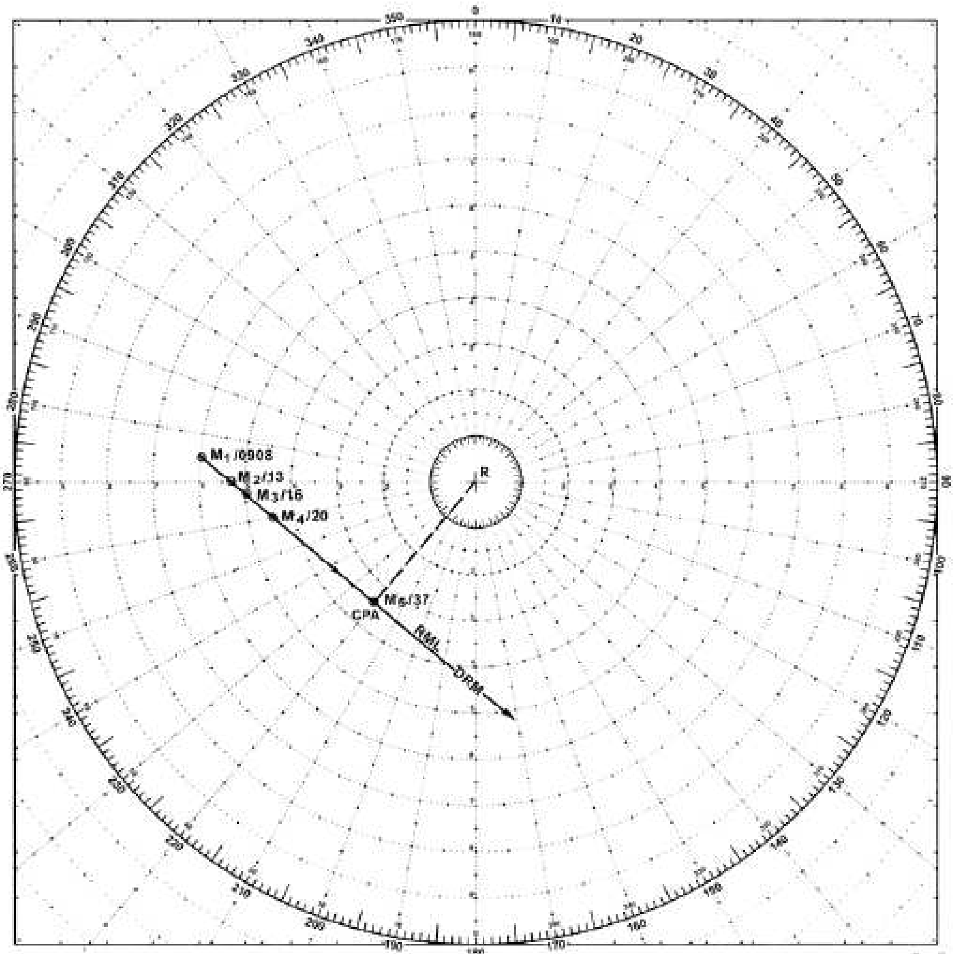
Situation: *Other ship M is observed as follows:*

Time	*Bearing*	*Range (Sm)*	*Rel Position*
09 08	*275*	*12,0*	*M1*
09 13	*270*	*10,7*	*M2*
09 16	*266*	*10,0*	*M3*
09 20	*260*	*9,0*	*M4*

Required: *(1) Direction of Relative Movement (DRM).*
(2) Speed of Relative Movement (SRM).

(3) Bearing and range at Closest Point of Approach (CPA).
(4) Estimated time of Arrival at CPA.

Solution: *(1) Plot and label the relative positions M1, M2, etc. using for distances und speeds the scale factor 2:1. The direction of the line M1 M4 through them is the direction of relative movement (DRM): 130°.*
(2) Measure the relative distance (MRM) between any two points on M1M4. M1 to M4 = 4Sm. Using the corresponding time interval (0920 - 0908 =12min), obtain the speed of relative movement (SRM)=4Sm/12min=20Kn.
(3) Extend M1M4. Provided neither ship alters course or speed, the successive positions of M will plot along the relative movement line. Drop a perpendicular from R to the relative movement line at M5. This is the CPA: 220°, 6,9Sm..
(4) Measure M1M5: 9,8Sm. With this MRM and SRM obtain time interval to CPA at 29 minutes. ETA at CPA= 0908 + 29 = 0937.



Answer: *(1) DRM 130°.*
(2) SRM 20 knots.
(3) CPA 220°, 6,9Sm.
(4) ETA at CPA 0937.

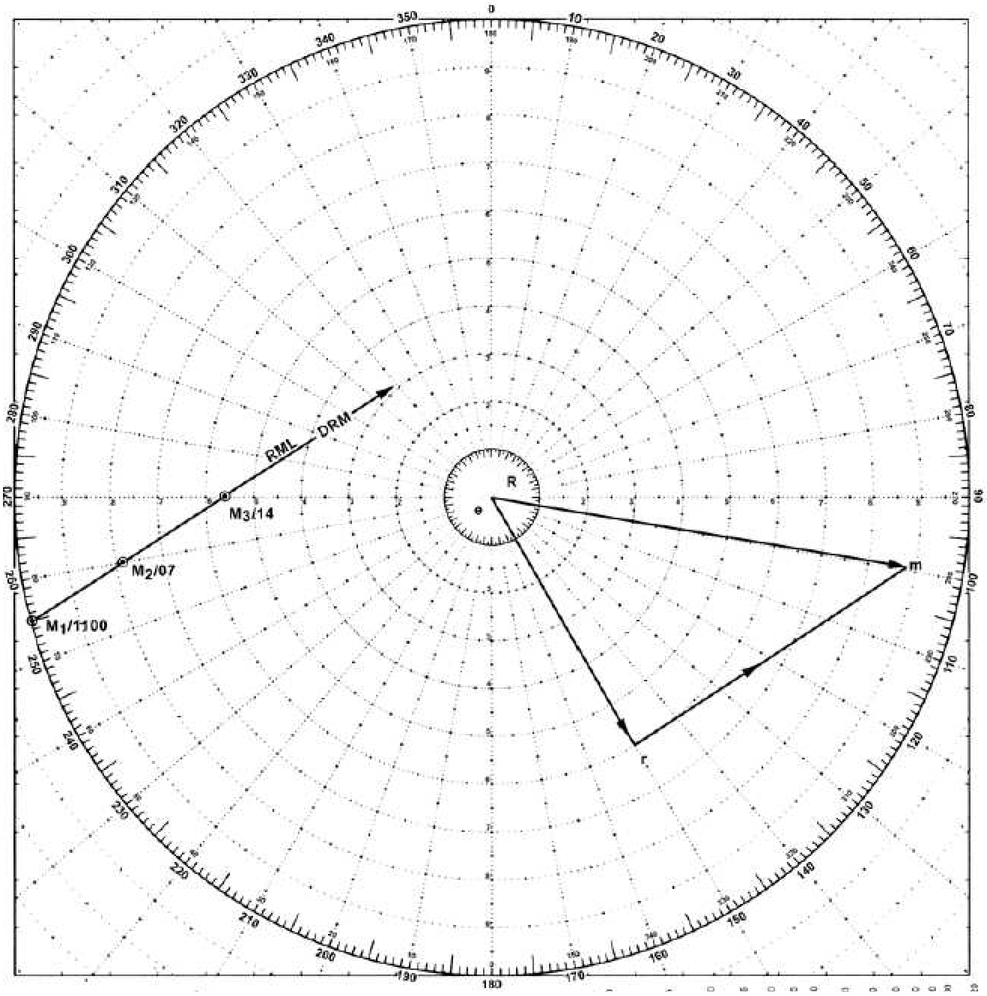
43622 Course and speed of other ship

Situation: *Own ship R is on course 150°, speed 18 knots. Ship M is observed as follows:*

Time	*Bearing*	*Range (Sm)*	*Rel Position*
11 00	*255*	*10,0*	*M1*
11 07	*260*	*7,9*	*M2*
11 14	*270*	*5,6*	*M3*

Required: *Course and speed of M*

Solution: *Plot M1, M2, M3and R using for distances the scale factor 1:1 und for speeds the scale factor 3:1. Draw the direction of relative movement line (RML) from M1 through M3. With the distance M1 M3(4,9Sm) and the interval of time between M1 and M3 (14min), the relative speed (SRM)of the other ship is 21knots. Draw the reference ship vector er corresponding to the course and speed of R. Through r draw vector rm parallel to and in the direction of M1 M3 with a length equivalent to the SRM of 21 knots. The third side of the triangle, em, is the velocity vector of the ship M: 099°, 27 Kn.*



Answer: *Course 099°, speed 27Kn*

43623 Course and speed to pass another ship at a specified distance

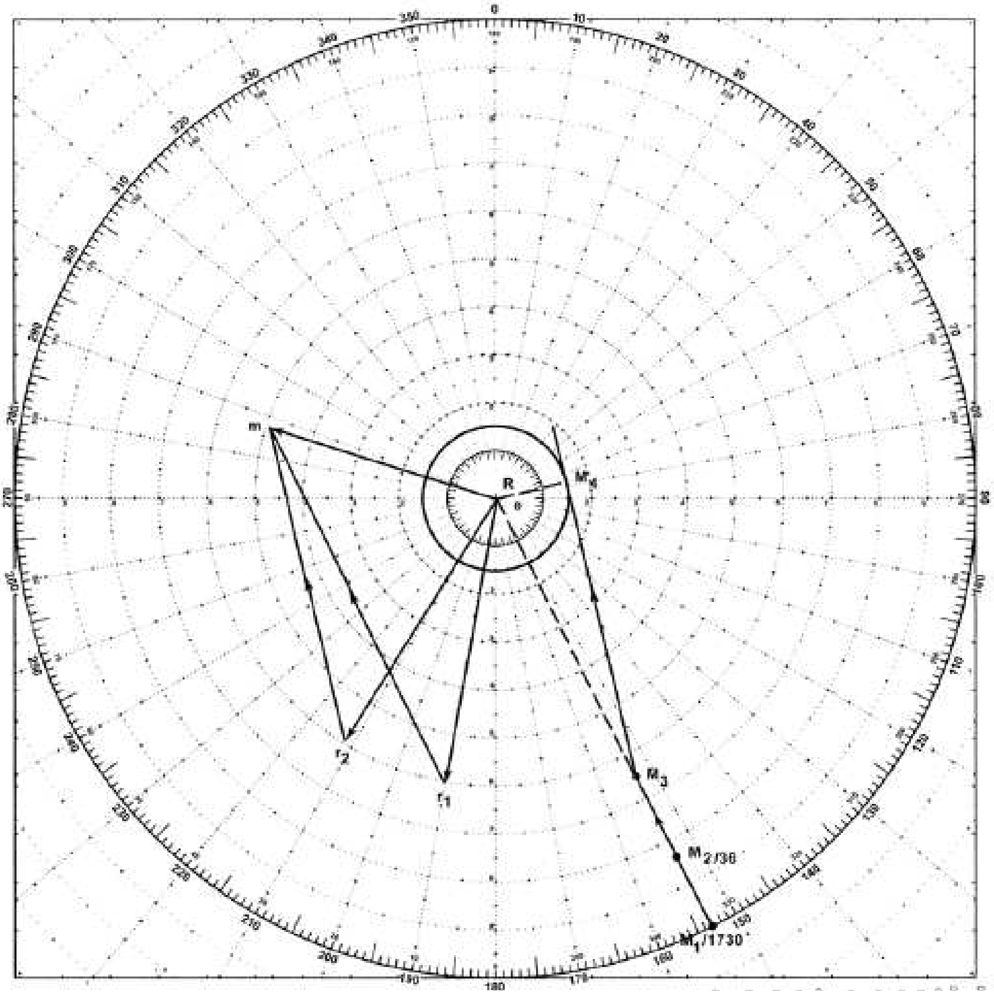
Situation 1: *Own ship R is on course 190°, speed 12 knots. Other ship M is observed as follows:*

Time	*Bearing*	*Range (Sm)*	*Rel Position*
17 30	*153*	*10,0*	*M1*
17 36	*153*	*8,35*	*M2*

Required: *(1) CPA*
(2) Course and speed of M

Situation 2: *It is desired to pass ahead of M with a CPA of 1,5 Sm*

Required 2: *(3) Course of R at 12 Kn if course is changed when range is 6,5 Sm.*
(4) At what time R shall change its course in order to maintain the range at 6,5 Sm
(5) Bearing and time of CPA.



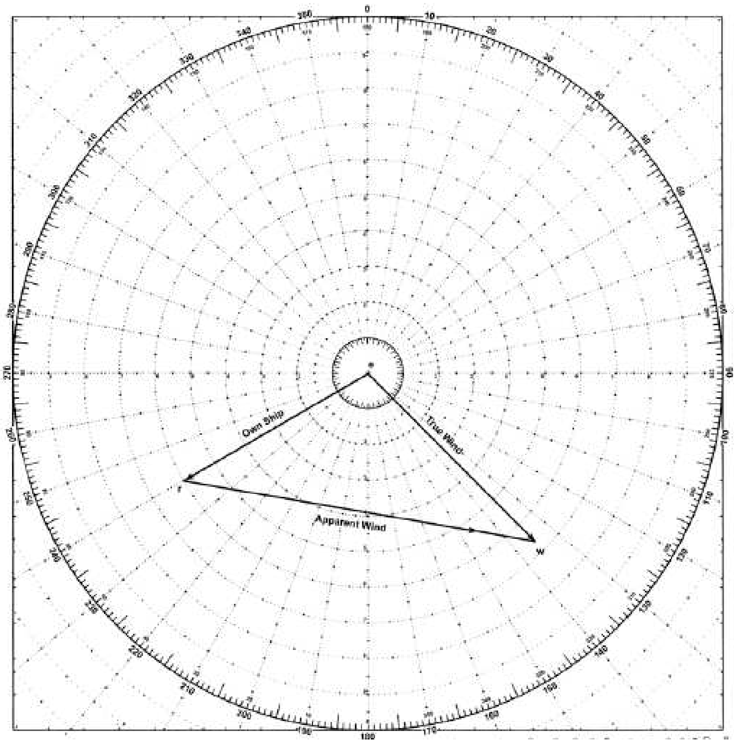
Solution: *(1) Plot M1, M2, and R. using for distances the scale factor 1:1 und for speeds the scale factor 2:1. Draw the relative movement line (RML) M1, M2 extended. Since the bearing is steady and the line passes trough R (CPA=0), the two ships are on collision courses.*

(2) Draw own ship's velocity vector er1 190°/12Kn. Measure the relative distance (M1M2=1,65Sm) travelled by M from 17 30 to 17 36 (6min) to obtain the relative speed SRM=16,5Kn. Draw the relative speed vector r1m parallel toM1M2 and 16,5 Kn in length. The velocity vector of M is em: 287°/10 Kn.
(3) Plot M3 bearing 153°, 6,5 Sm from R. With R as the centre describe a circle of 1,5 Sm radius, the desired distance at CPA. From M3 draw a line tangent to the circle M4. This places the relative movement line of M (M3M4) the required minimum distance of 1,5 Sm from R. Trough m, draw r2m parallel to and in the direction ofM3M4 intersecting the 12 Kn circle (speed of R) at r2. Own ship velocity vector is er2: 212°/12 Kn.
(4) M travelling with a relative speed SRM=16,5 Kn will cover the relative distance M2M3=8,35-6, 5=1,85 Sm within 7min i.e. at 17 43.
(5) Using the relative speed vector of r2m=13,4 Kn and the distance from M3 to CPA: M3M4=6,4 Sm the elapsed time from M3 to M4 can be determined to be 28 min. The time of CPA is therefore 17 43 + 00 28 = 18 11.

Answer: *(1) M and R are on collision courses.*
(2) Course 287°, speed 10Kn
(3) Course 212°
(4) Time at M3: 17 43
(5) Bearing 076°, time of CPA 18 11

43624 Determination of true wind

Situation: *A ship is on course 240°, speed 18 Kn. The relative wind across the deck is 30 Kn from 040° relative.*



Required: *Direction and speed of true wind.*

Solution: *Plot er, the ships vector of 240°, 18 Kn. Convert the relative wind to apparent wind by plotting rw 040° relative to ships head which results in a true direction of 280° T. Plot the apparent wind vector (reciprocal of 280° T, 30 Kn) from the end of the vector er. Label the end of the vector w. The resultant vector ew is the true wind vector of 135°, 20 Kn (winds course and speed). The true Wind , therefore, is from 315°.*

Answer: *True wind from 315°, speed 20 kn.*

PART 4

(Electronic navigation)

Chapter 4

(Standard's for electrical interfaces)

4410 Purpose

Today electronics touches almost every aspect of navigation. Satellite systems, electronic charts and radar aids to navigation all require an increasingly sophisticated electronic suite and the expertise to manage them. The effort required to manage a great number of electronic boxes is rapidly decreasing with the introduction of adequate communication links enabling each electronic box to receive information from any other box, or to transmit information to any other box without any manual intervention of the navigator.

Considering the fact that the electronic environment on board of a vessel consists of equipment provided from different sources, it is obvious that in order to be able to establish a communication link as defined above, one should first define and agree with the equipment manufacturers suitable hardware and software standards applicable for said link. The standards which are widely used today for marine data busses, and which define the electrical interface and data protocol for communication between marine instrumentation are the so called NMEA standards.

Nevertheless as many people want to connect e.g. a GPS receiver to a computer, there is a need to have some knowledge about the RS-232 interface in order to be able to connect said equipment to the serial ports of the computer.

4420 The National Marine Electronics Association (NMEA)

The National Marine Electronics Association is a non-profit association composed of manufacturers, distributors, dealers, educational institutions, and others interested in peripheral marine electronics occupations. NMEA has become a developer, maintainer and distributor of various documents and standards related to the marine electronics industry. NMEA standards have been accepted as the common practice for how to share specific data information between competing entities or companies since the late 1970s.

NMEA Standards Serve the public safety. They have been developed from manufacturers, private and government organizations, dealers and equipment operators in order to:

- facilitate the public interest in the interconnection and interchangeability of equipment, to
- minimize misunderstanding and confusion between manufacturers, and to
- Assist purchasers in selecting compatible equipment

The National Marine Electronics Association is the unifying force behind the entire marine electronics industry, bringing together all aspects of the industry, and is furthermore dedicated to the education and advancement of the marine electronics industry and the market which it serves.

4430 NMEA Capabilities and performance standards

NMEA established until now three data bus specifications, namely the NMEA-180, 182 and 183 and issued in 2002 the so called NMEA-2000 specification.

- The NMEA-180, 182 and 183 standards are unidirectional interfaces allowing a single talker (Tx) and several listeners (Rx) on one circuit. Data buses designed to satisfy said standards are not communication networks. They are serial data interfaces, and are used as a universal method for data exchange between devices. Their maximum data transfer rate does not exceed 4,8 Kilobits/sec which leads to a transfer of 6-8 messages/sec.

- The NMEA-2000 standard contains the requirements of a serial data communications network to inter-connect marine electronic equipment on vessels. It is multi-master and self configuring, and there is no central network controller. Equipment designed to this standard will have the ability to share data, including commands and status with other compatible equipment over a single channel.

Although it is expected that in the future, the NMEA-180, 182 and 183 standards will be replaced by NMEA-2000, it is important to understand their physical lay out and their performance characteristics, simply because today most of the electronics on board of a vessel are interconnected using the specification of one of these standards.

4440 NMEA-180, 182 and 183 interface definitions

The recommended interconnect wiring is a shielded twisted pair, with the shield grounded only at the talkers side. The standards do not specify the use of any particular connector.

The NMEA-0180 and 0182 standards say that the talker output maybe RS-232, or from a TTL buffer, capable of delivering 10 mA at 4 V. The open collector TTL buffer contains a 680 ohm resistor to +12 V, and a diode to prevent the output voltage from rising above +5.7 V.

NMEA-0183 accepts this, but recommends that the talker output contains a differential system, having two signal lines, A and B. The voltages on the "A" line correspond to those on the older TTL single wire, while the "B" voltage are reversed (while "A" is at +5, "B" is at ground, and vice versa)

In either case, the recommended receive circuit uses an opto-isolator with suitable protection circuitry. The input should be isolated from the receiver's ground. In practice, the single wire "A", may be directly connected to a computer's RS-232 input.

4450 NMEA-180 and 182 performance definitions

NMEA-0180 and 0182 are very limited, and just deal with communications from a Loran-C (or other navigation receiver, although the standards specifically mention Loran), and an autopilot. The specifications for both standards are nearly identical. However, equipment designed to operate in accordance with NMEA-180 are using the "simple" format described below, while those designed to satisfy the requirements of NMEA-180 will use the "complex" format.

4451 Simple data format

The simple format consists of a single data byte transmitted at intervals of 0.8 to 5 seconds, at 1, 2 K baud with odd parity. Bits 5 - 0 give the cross-track error in units of 0.1 μsec or 0.01 nautical miles. The error is given in offset binary, with a count of 1 representing full scale right error, 32 (hex 20) for on course, and 63 (hex 3f) full scale left error. Bit 6 is a 1 if the data is valid, and bit 7 is 0 to indicate the simple data format.

4452 Complex data format

The complex format consists of a data block of 37 bytes of (mostly) readable ASCII text giving cross-track error, bearing to waypoint, present Latitude and Longitude, and a binary status byte (Ref. Figure 4450).

Byte	Data	Interpretation
1	$	
2	M	Device.
3	P	Address.
4	K=Kilometres or N=Nautical miles or U=Microseconds	Cross track error units.
5-8	0-9	Cross track error value.
9	L or R	Cross track error position.
10	T or M	True or magnetic bearing.
11-13	0-9	Bearing to next waypoint.
14-23	12D34’56”N or 12D34.56’N	Present latitude
24-34	123D45’56”W´ or 123D45.67”W	Present longitude
35	Non ASCII status byte	
	Bit 0=1	Manual cycle lock.
	1=1	Low SNR.
	2=1	Cycle jump.
	3=1	Blink
	4=1	Arrival alarm.
	5=1	Discontinuity of TD’s.
	6=1	Always.
36	“NUL”	Character (hex80) (reserved status byte)
37	“ETX”	Character (hex83)
Any unavailable data is filled with "NUL" bytes.		

Figure 4450 NMEA-182 data form

The data block shall be sent at intervals of 2 to 8 sec. All bytes in the complex format have bit7 = 1 to distinguish them from the simple format. It is permissible for a sending device to send both simple and complex data, and even to send a "simple" data byte in the middle of a "complex" data block.

4460 NMEA-183 performance definitions

Under the NMEA-0183 standard, all characters used are printable ASCII text (plus carriage return and line feed). NMEA-0183 data is sent at 4,8 Kbaud.

4461 General sentence format

The data is transmitted in the form of "sentences". Each sentence starts with a "$", a two letter "talker ID", a three letter "sentence ID", followed by a number of data fields separated by commas, and terminated by an optional checksum, and a carriage return/line feed.

A sentence may contain up to 82 characters including the "$" and CR/LF.

- If data for a field is not available, the field is simply omitted, but the commas that would delimit it are still sent, with no space between them.
- Since some fields are variable width, or may be omitted as above, the receiver should locate desired data fields by counting commas, rather than by character position within the sentence.
- The optional checksum field consists of a "*" and two hex digits representing the exclusive OR of all characters between, but not including, the "$" and "*". A checksum is required on some sentences.

Some common talker IDs are:

- GP Global Positioning System receiver
- LC Loran-C receiver
- OM Omega Navigation receiver
- II Integrated Instrumentation (eg. AutoHelm Seatalk system)

4462 Standard sentences

A talker typically sends a group of sentences at intervals determined by the unit's update rate, but generally not more often than once per second. Characters following the "*" are a checksum. Checksums are optional for most sentences, according to the standard. Below there are some examples of typical NMEA-183 sentences.

44621 Recommended minimum sentence for global positioning system receivers.

The **GPRMC**-sentence (**RMC** = Recommended Minimum sentence C) is a recommendation for the minimum information a GPS receiver should make available.

```
                                                                              (11)
                      (1)   (2)    (3)   (4)    (5)    (6) (7) (8)  (9)   (10)
(12)(13)
                       |     |      |     |      |      |   |   |    |     |  |  |  |
 $GPRMC,191410,A,4735.5634,N,00739.3538,E,0.0,0.0,181102,0.4,E,A*19
```

Field number: (1) Position fix obtained at 19:14:10 UTC.
(2) Data quality. A = Valid data; V = Invalid data.
(3) Latitude=47° 35,5634´.
(4) Sign of latitude (N=North or S=South)
(5) Longitude=007° 39,3538´.
(6) Sign of longitude (E=East or W=West)
(7) SOG in Kn.
(8) COG
(9) Date 18.11.02
(10) Magnetic variation = 0,4°
(11) Sign of magnetic variation (E=East or W=West)
(12) Modus (Implemented with NMEA version 2.3): A=Autonomous; D=Differential; E=Estimated; N=Not valid; S= simulator
(13) Checksum

44622 Autopilot sentences.

There are two different formats for autopilot sentences in use: The APA and the APB where APB as described below is the most comprehensive sentence.

```
 (1)(2)(3)  (4) (5) (6) (7) (8)  (9)  (10)  (11)(12)(13)(14)(15)
  |  |  |    |   |   |   |   |    |    |     |   |   |   |   |
$--APB,A,A,x.x,R,N,A,A,x.x,M,c--c,x.x,T,x.x,M*hh<CR><LF>
```

Field number: (1) Status: V=LORAN-C Blink or NSR warning.
A= General warning flag or other navigation systems when a reliable fix is not available.
(2) Status: V=LORAN.C cycle lock warning flag.
A= OK or not in use.
(3) Cross track error magnitude.
(4) Direction to steer, L or R (Left or Right).
(5) Cross track error unit, N=Nautical miles.
(6) Status: A=Arrival circle entered.
(7) Status: A=Perpendicular passed at waypoint.
(8) Bearing origin to destination.
(9) M=Magnetic or T=True suffix for field number (8).
(10) Destination waypoint ID.
(11) Bearing, present position to destination.
(12) M=Magnetic or T=True suffix for field number (11).
(13) Heading to steer to destination point.

(14) M=Magnetic or T=True suffix for field number (13).
(15) Checksum.

44623 Sentence for bearing and distance to waypoint.

For bearing and distance to waypoint two sentences are used, one for the great circle **(BWC),** as exhibited in the example below**,** and one for the Rhumb line **(BWR)** navigation. However both sentences have the same format.

(1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11)(12)
(13)
| | | | | | | | | | | | |

$--BWC,225444,4917.24,N,12309.57,W,051.9,T,031.6,M,001.3,N,004*29

Field number: (1) UTC time of fix 22:54:44.
(2) Latitude of the waypoint= 49° 17,24´.
(3) Sign of the waypoint latitude (N=North or S=South).
(4) Longitude of the waypoint= 123° 9,57´.
(5) Sign of the waypoint longitude (E=East or W=West).
(6) Bearing to waypoint=51,9°.
(7) Indicates that the bearing in field number (6) is a true bearing.
(8) Bearing to waypoint=31,6°.
(9) Indicates that the bearing in field number (8) is a magnetic bearing.
(10) Magnitude of the distance to waypoint.
(11) The unity of field number 10 is nautical miles.
(12) Waypoint ID.
(13) Checksum.

4463 Proprietary sentence formats and bus systems

The standard allows individual manufacturers to define proprietary sentence formats. These sentences start with "$P", then a 3 letter manufacturer ID, followed by whatever data the manufacturer wishes, following the general format of the standard sentences.

A Garmin proprietary sentence may start as follows: “$PGRMZ,” . "P" denotes proprietary, "GRM" is Garmin's manufacturer code, and "Z" indicates the specific sentence type.

Autohelm Seatalk is a proprietary bus for communications between various instruments. Some of the instruments can act as NMEA-0183 talkers or listeners. Data received from an external NMEA-0183 device will, if Seatalk understands the sentence, be re-transmitted, but not necessarily in the same sentence type.

The specific sentences sent will depend on the data available on the Seatalk bus (i.e. sentences containing wind speed and direction will only be sent if the system includes a wind instrument). Note that NMEA data can only be sent to, or received from, a SeaTalk system using AutoHelm's NMEA<->SeaTalk interface box, or those instruments that provide an NMEA-0183 interface. **SeaTalk itself is not compatible with NMEA, and cannot be read with a normal PC serial port.**

4470 RS-232 connections

Although this is not really related to NMEA, many people want to connect a GPS to a computer, so need to know about the RS-232 serial ports on a computer.

The RS-232 standard defines two classes of devices that may communicate using RS-232 serial data - Data Terminal Equipment (DTE), and Data Communication Equipment (DCE). Computers and terminals are considered DTE, while modems are DCE. The standard defines pinouts for DTE and DCE such that a "straight through" cable (pin 2 to pin 2, 3 to 3, etc) can be used between a DTE and DCE. To connect two DTE's together, you need a "null modem" cable, that swaps pins between the two ends (e.g. pin 2 to 3, 3 to 2).

Unfortunately, there is sometimes disagreement whether a certain device is DTE or DCE, hence there is a standard RS-232 disclaimer:

If it doesn't work, swap pins 2 and 3!

The standard RS-232 connector is a 25 conductor DB-25, although many PCs (and some other equipment) now use a 9 pin DE-9 (often incorrectly called DB-9). The Pinout is as exhibited in the figure below

Serial Port Connections			
Computer (DTE)		**Signal**	**Modem**
DB-25	**DE-9**		**DB-25**
2	3	Tx Data	2
3	2	Rx Data	2
4	7	Request to send	4
5	8	Clear to send	5
6	6	Data set Ready	5
7	5	Signal ground	7
8	1	Data Carrier Detect	8
20	4	Data Terminal Ready	20
22	9	Ring Indicator	22

Figure 4470 RS-232 Pinout

For NMEA-0183 interfacing, we are only concerned with Rx Data, signal ground (and possibly Tx Data, if we want the computer to talk to the GPS)

4480 Troubleshooting on NMEA-183 interface

First check that the talker (usually GPS) can send NMEA-0183, and determine what sentences it sends. Also, verify that the listener understands NMEA-0183, and that it understands the sentences the talker is sending. In some cases the same information may be sent in two or more different sentences. If the talker and listener don't both use the same sentences, there will be no communication. It may be possible to change the sentences sent by the talker, to match those understood by the listener.

Next, check that the talker is indeed set to send NMEA-0183 data. Some talkers may have provision to send NMEA-0180 or 0182, or some proprietary format.

A computer, using a convenient terminal program (mostly Windows Terminal) set to 4800 baud, can be used to monitor the NMEA data, and confirm what sentences are sent, and that the data is in the correct format. Verify that the wiring is correct - that the talker data output is connected to the listener data input, and that a signal ground line is connected between the two pieces of equipment.

If you have multiple listeners connected to a single talker, you may be overloading the talker port. Try connecting only one listener at a time.

On any NMEA-0183 circuit, there can only be one talker. If you must have more than one talker, and one of the talker devices can also act as a listener, you may be able to connect things "in series", so a talker-only output is connected to a listener/talker input, and the listener/talker output is connected to other listeners. However, some listener/talker devices may reformat the data, or only pass data they understand. (The Autohelm Seatalk system does this, and claims the data as it's own, starting all output sentences with "$II").

Particularly with older equipment, the equipment may claim to comply with NMEA-0183, but in fact have an error in the data format. This sort of problem can be verified by capturing the NMEA-0183 data on a computer, and comparing the data formats with specified.

4490 NMEA-2000

The standard contains the requirements of a serial data communications network to inter-connect marine electronic equipment on vessels. It is a multi- talker and multi- listener system which acts as a self configuring multi-master, without any central network controller. Equipment designed to this standard will have the ability to share data, including commands and status with other compatible equipment over a single channel

The standard offers a complete network protocol, it represents an “open” standard for electronics, electrical and engine data all on the same network, and facilitates exchange of data between multiple manufacturers equipment simultaneously.

With 250 Kbits/sec, the single channel parallel NMEA-2000 bus, is 50 times faster than the NMEA-183 high speed standard, and is designed to connect on board equipment installed up to 200 m apart. The standard mandates a physical layer consisting off standard connectors, cables and terminators

The standard uses a Controller Area Network (CAN) protocol developed by Intel and Bosch for use in automotive, in control processes for industrial applications and in factory automation. The CAN Protocol has been proven to be a robust error free protocol, which automatically determines repeated errors, and which offers the incorporation of embedded priority messaging for collision avoidance purposes and fast through put of critical messaging.

PART 5

(Navigational mathematics)

Chapter 1

(Terms and conventions)

5110 The Circle

5111 Definitions

A ***circle*** is a simple shape of Euclidean geometry consisting of points in a plane which are the same distance from a given point called the ***centre***. The common distance of the points of a circle from its centre is called its ***radius***, whilst the line segment whose endpoints lie on the circle and which passes through the centre of the circle is called the ***diameter***. The length of the diameter is twice the length of the radius. The length of the perimeter of a circle is called the ***circumference***.

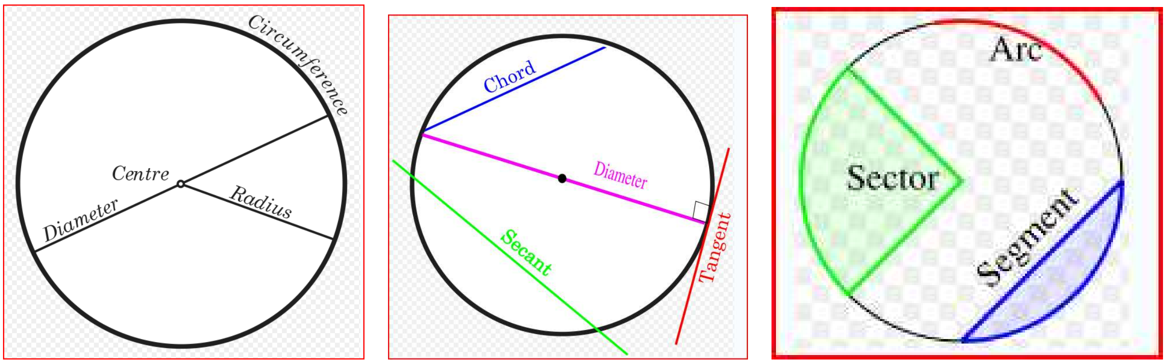


Fig. 5111 Circle illustrations

A ***chord*** of a circle is a line segment whose two endpoints lie on the circle. The diameter is the largest chord in the circle. A ***tangent*** to a circle is a straight line touching the circle at a single point and is always perpendicular to the diameter. A line cutting the circle at two points is called the ***secant***. An ***arc*** is any continuous part of the circle´s perimeter. A ***sector*** is a region bounded by two radii and an arc lying between the radii and a ***segment*** is a region bounded by a chord and an arc lying between the chord's endpoints.

5112 The length of circumference

As a consequence of the similarity of all circles the ratio between the circumference and the diameter of a circle is regardless of the circle's size constant. This mathematical constant ***(π)*** – with an approximate value of 3,1416 - is an irrational number which means that its value can not be expressed exactly as a fraction m/n, where m and n are integers, and therefore its decimal representation never ends or repeats. It is also a transcendental number, which means that no finite sequence of algebraic operations on integers (powers, roots, sums, etc.) can be equal to its value.

Thus the length of the circumference (c) is related to the diameter (d) by

$$c=\pi d$$

or equivalent to the radius (r) by

$$c=2\pi r$$

5113 Area enclosed

The circle is the plane curve enclosing the maximum area (A) for a given arc length and can be calculated by:

$$A=\pi r^2$$

Equivalently, denoting diameter by d,

$$A=\frac{\pi d^2}{4}$$

An approximate solution for the area enclosed by a circle can also be obtained using Fig. 5113 below.

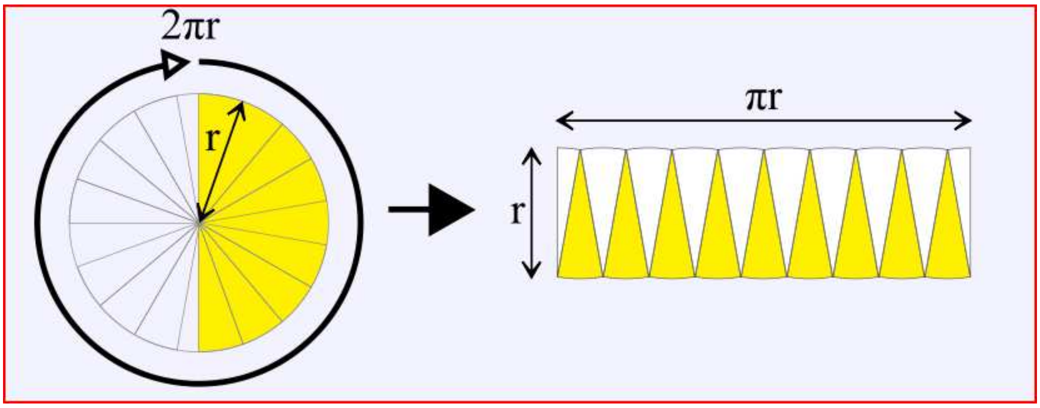


Fig. 5113 Area enclosed by a circle

It is obvious that increase of the number of the sectors (by a reduction of their arc), leads to a nearly rectangular plane curve with a width of r and a length of πr, which consequently leads to an area enclosed $A=\pi r^2$.

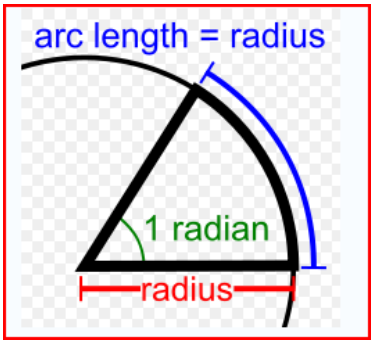
5114 Radian

One radian is the angle subtended at the center of a circle by an arc that is equal in length to the radius of the circle.

More generally, the magnitude in radians of any angle subtended by two radii is equal to the ratio of the length of the enclosed arc to the radius of the circle; that is,

$$\alpha = b/r$$

where **α** is the subtended angle in radians, **b** is arc length, and **r** is radius. Conversely, the length of the enclosed arc is equal to the radius multiplied by the magnitude of the angle in radians; that is, $s = r\alpha$.



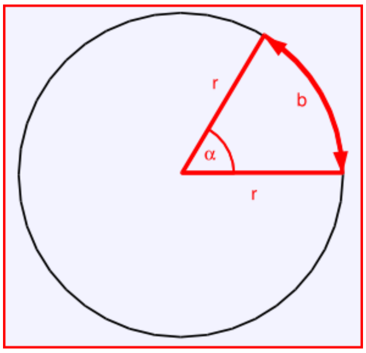


Fig. 5114 Definition of radian

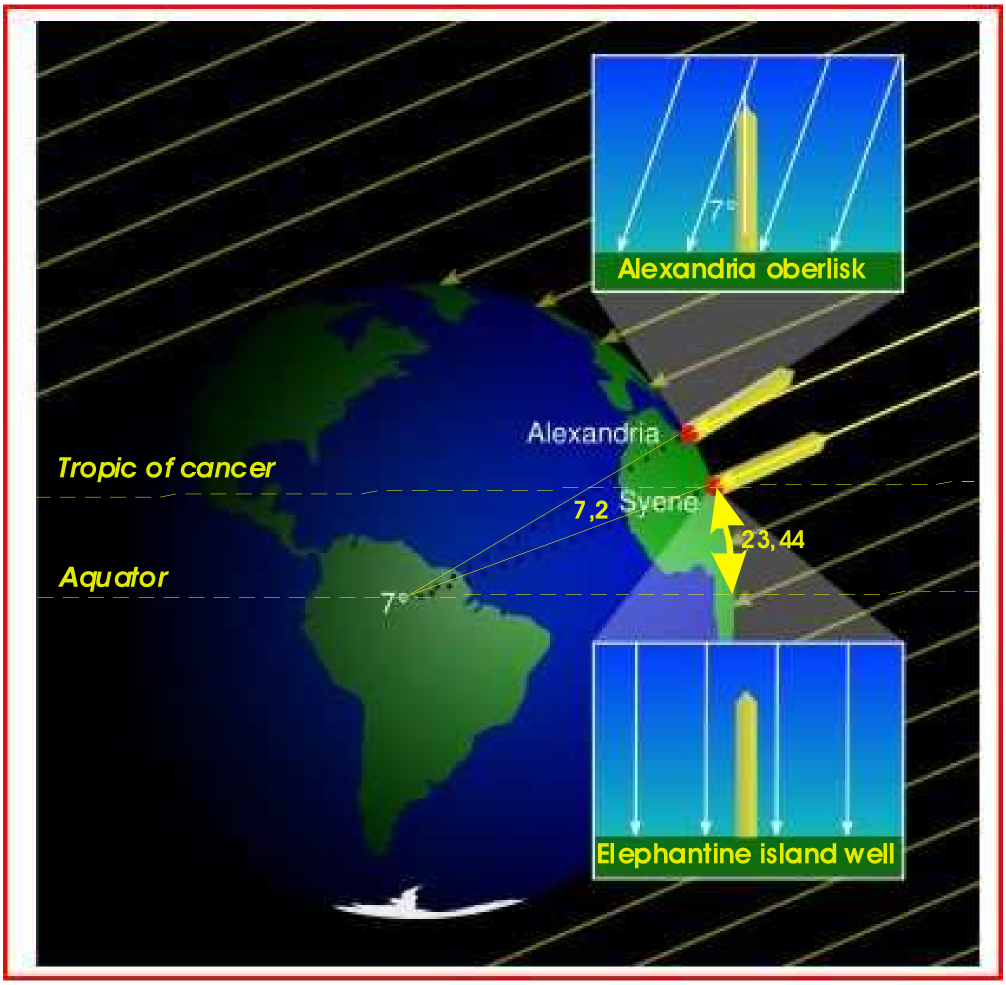
It follows that the magnitude in radians of one complete revolution (360 degrees) is the length of the entire circumference divided by the radius, or $2\pi r /r$, or 2π. Thus 2π radians is equal to 360 degrees, meaning that one radian is equal to $180/\pi$ degrees (about 57, 2958°).

Example: *Find the circumference of the earth based on Eratosthenes measurements and assumptions.*

Answer: *Based a on the assumption the ancient Egyptian city of Swenet (known to the Greeks as Syene, and in the modern days as Aswan) lies on the Tropic of Cancer, Eratosthenes knew that on the summer solstice at the local apparent noon, the sun would appear at the Zenith, directly overhead of this city.. In order to be able to determine the point of time the sun would reach its Zenith in said place, Eratosthenes sank therefore a well on the Elephantine Island providing a mirror image of the sun during its culmination.*

Assuming the distance of his home town Alexandria was 5.000 Stadia due north to Syene, Eratosthenes erected an obelisk of a known height in Alexandria in order to measure the shadow of the obelisk during the culmination of the sun in Syene on the summer solstice.

From this experiment he obtained an angle of elevation of the sun in Alexandria of 07° 12´ south of the Zenith in Syene, which is also the value of the angle subtended by the earth radii pointing to Syene and Alexandria. From § 5114 above it is obvious that the earth radius(r) is equal to the ratio of the

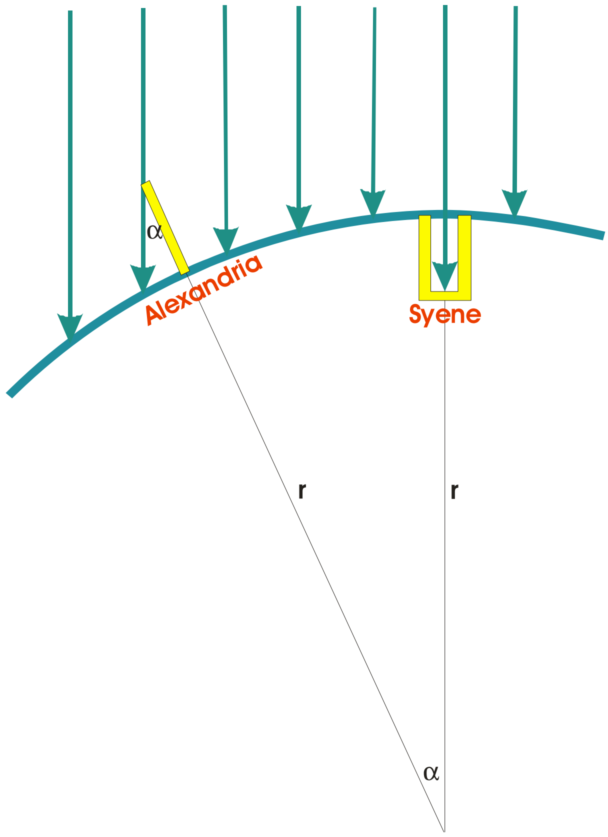


length of the arc enclosed by the earth radii pointing to Syene and Alexandria (b) to the magnitude in radians of the angle(α) subtended by said radii.

i.e.: $r = \dfrac{b*180}{\alpha*\pi}$ *: The circumference of the earth can therefore calculated as follows:*

$$C = 2*\pi*r = 2*\pi\frac{b*180}{\alpha*\pi} = b\frac{360}{\alpha}$$

Eratosthenes estimated the distance between the two cities was 5.000 stadia which lead to an earth circumference of 250.000 stadia. The exact size of the stadion he used is frequently argued. Assuming he did use the Egyptian stadium (157,5m) instead of the common Attic stadium (about 185m), his measurement turns out to be C=39.375 Km, an error of less than 1%.



Although Eratosthenes method was well founded, the accuracy of his calculation was inherently limited. The accuracy of Eratosthenes measurement would have been reduced by the fact that Syene is 39 Sm north of the Tropic Cancer and not directly south of Alexandria. However there are other sources of experimental error. The greatest limitation to Eratosthenes method was that, in antiquity, overland distance measurements by the odometer were not very reliable, and measurements travelling primarily by boat along the non-linear Nile were extremely difficult. So the accuracy of Eratosthenes size of the circumference of the earth is surprising..

PART 5

(Navigational mathematics)

Chapter 2

(Coordinate Systems)

5210 Fundamentals

In order to describe the space position of a body one needs a coordinate system defined by:

- a zero point
- a reference direction and
- a reference plane

There are two coordinate systems in use called the **Cartesian coordinate system** employing orthogonal coordinates (ref Fig. 5210), and the **Spherical coordinate system** employing polar coordinates (ref Fig. 5211)

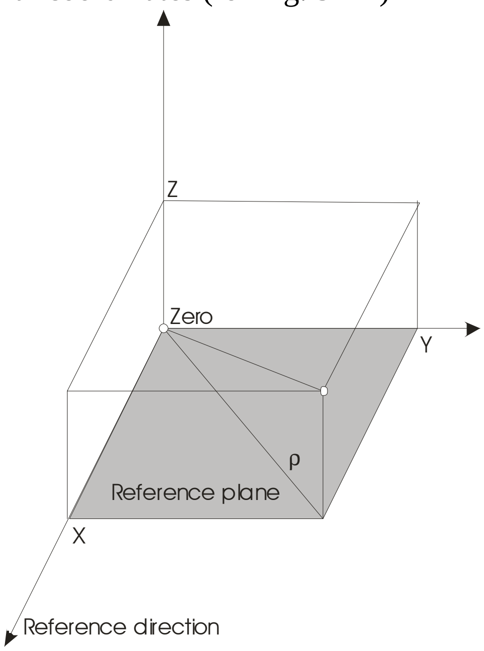


Fig. 5210 description of a point by means of orthogonal coordinates.

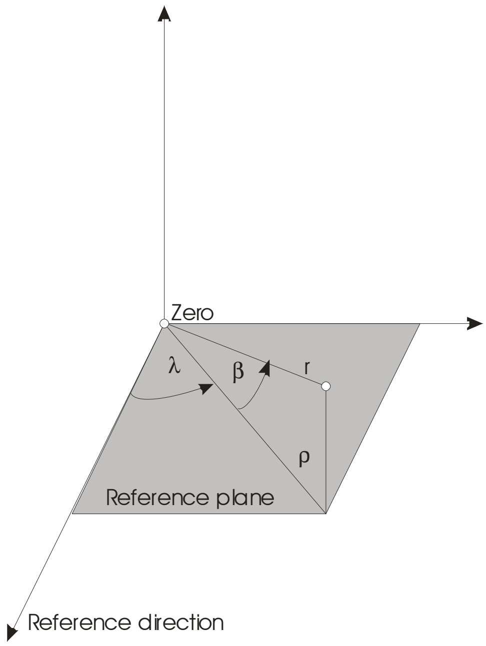


Fig. 5211 description of a point by means of polar coordinates.

The Cartesian coordinate system consist of three axes (x-, y-, and z-axis) all meeting at the zero point. The reference direction is defined by the x-axis, whilst the reference plane is the x-y-surface. The coordinates describing a certain point in the space are nothing else than the lengths of the projection of said point on the individual axes.

In Polar coordinate system the position of a body is defined by the angle between the reference plane and the connection from zero to the body (β), the angle between the reference direction and the projection of the connection from zero to the point on the reference plane (λ) and the distance r from zero to the body.

In principal both coordinate systems exhibited above are equivalent. The polar coordinates however offer in the astronomy the advantage of limiting the information concerning the position of a body to only two coordinates, if e.g. there is no information about the distance to the body.

5220 Transformation of coordinates

The formulas exhibited below have been derived using Fig. 5210 and Fig. 5211 above. Angles are always expressed in degrees. Furthermore it is taken to be granted that both coordinate systems refer to the same zero point, the same reference direction and the same reference plane.

5221 Transformation of Spherical to Cartesian coordinates

The following equations can be used to transform polar coordinates of a body to orthogonal coordination system.

$$x = r * \cos\beta * \cos\lambda$$
$$y = r * \cos\beta * \sin\lambda$$
$$z = r * \sin\beta$$

5222 Transformation of Cartesian to Spherical coordinates

In this paragraph the equations required for the transformation of orthogonal coordinates of a body to polar coordination system are derived. With $\rho = \sqrt{x^2 + y^2}$ the distance of the body from zero is calculated as Follows:

$$r = \sqrt{x^2 + y^2 + z^2}$$

For the calculation of β the following specific cases for ρ and z have to be taken into account.

For $\rho \neq 0$:	$\beta = arctg(z / \rho)$
For $\rho = 0$ and $z > 0$:	$\beta = +90°$
For $\rho = 0$ and $z < 0$:	$\beta = -90°$
For $z = 0$:	$\beta = 0°$

For the calculation of λ the following specific cases for x and y have to be taken into account.

For $x = 0$ and $y = 0$:	$\lambda = 0°$
For $x \geq 0$ and $y \geq 0$:	$\lambda = \mathrm{arctg}(y/x)$
For $x \geq 0$ and $y < 0$:	$\lambda = 360° + \mathrm{arctg}(y/x)$
For $x < 0$:	$\lambda = 180° - \mathrm{arctg}(y/x)$

PART 5

(Navigational mathematics)

Chapter 3

(Calculations and conversions)

5310 Plane trigonometric functions

In figure 5310 below OR is assumed to be a *unit radius*. By convention the sign of OR is always positive. This radius is assumed to rotate counter clockwise through 360° from the horizontal position at 0°, the positive direction along the X-axis. Ninety degrees (90°) is the positive direction along the Y-axis.

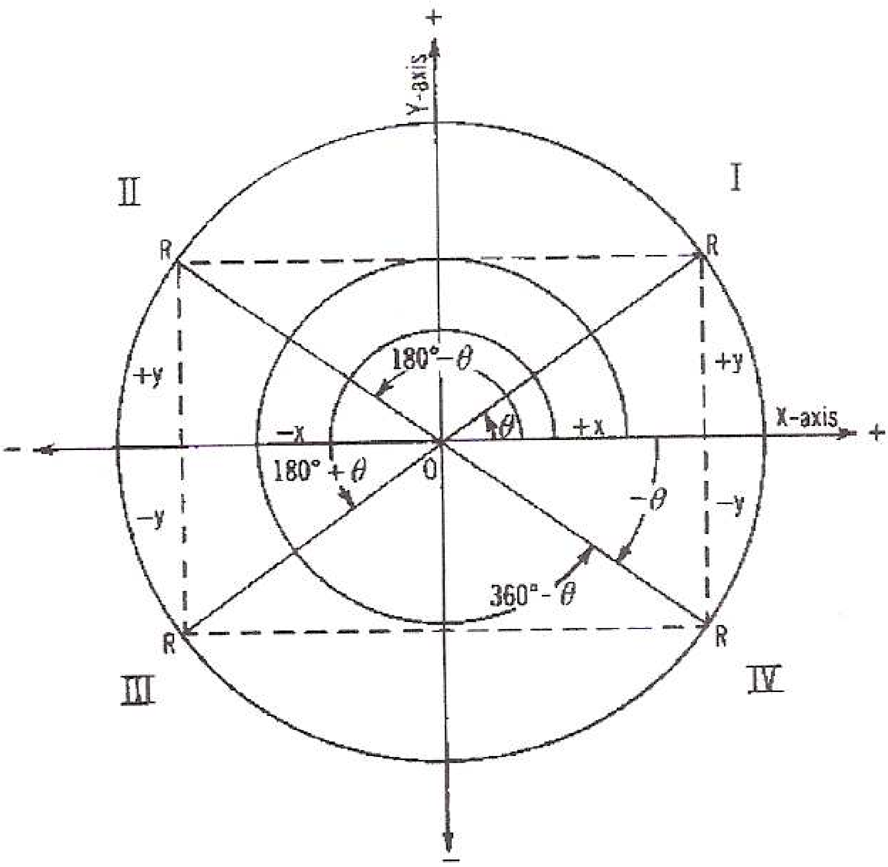


Figure 5310 The functions in various quadrants

The following basic relationships can be extracted from the first (I) quadrant of the figure 5310 above.

- The numerical value of the sin of an angle is equal to the projection of the *unit radius* on the Y-axis.

$$\sin\vartheta = +y$$

- The numerical value of the cos of an angle is equal to the projection of the *unit radius* on the X-axis.

$$\cos\vartheta = +x$$

- The numerical value of the tg of an angle is equal to the ratio of the projections of the *unit radius* on the Y and X-axes.

$$tg\vartheta = \frac{+y}{+x}$$

5311 Basic trigonometric reduction formulae

The following basic trigonometric reduction formulae can be derived from figure 5110 above.

Function	β=90°± α	β=180°± α	β=270°± α	β=360°– α
sinβ	cosα	∓sinα	-cosα	-sinα
cosβ	∓sinα	-cosα	± sinα	cosα
tgβ	∓ctgα	± tgα	∓ctgα	- tgα
Ctgβ	∓ctgα	± ctgα	∓ctgα	- ctgα

5312 Important formulae of the plane trigonometry

The equations exhibited below have as well been derived from figure 5310 above, and are expressions of the functions of one and the same angle.

$\sin^2\alpha + \cos^2\alpha = 1$ $\quad \frac{\sin\alpha}{\cos\alpha} = tg\alpha$ $\quad \frac{\cos\alpha}{\sin\alpha} = ctg\alpha$ $\quad$ tgα*ctgα=1

For further detail relationships of plane trigonometric functions refer to Appendix F, which contains information obtained from the mathematic compendium of Bronstein- Semendjajew (Part II, Chapter IV, Para A, Subpara 2).

5320 Solving plane triangles

Solving a right plane triangle is trivial and will therefore not be discussed here. The following laws are helpful in solving oblique plane triangles.

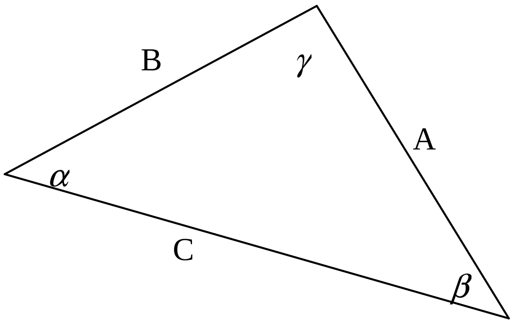


Figure 5320. An oblique plane triangle

Sinus law: $$\frac{A}{\sin\alpha} = \frac{B}{\sin\beta} = \frac{C}{\sin\gamma}$$

Cosinus law: $$A^2 = B^2 + C^2 - 2 * B * C * \cos\alpha$$

To solve a second order equation $a*x^2 + b*x + c = 0$ use the following law:

$$x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4 * a * c}}{2 * a}$$

5330 Spherical trigonometry

Cutting a sphere with a plane going trough its centre, we always obtain on the surface of the sphere great cycles representing the shortest distance between two points on the spheres surface. Three great cycles create on the surface of the sphere more than one spherical triangle. The most important characteristic of a spherical triangle is, that the sum of its angles is always greater than 180°.

For solving spherical triangles use the basic equations (1) to (4) shown in § 3440. For further detail relationships of Spherical trigonometric functions refer to the mathematic compendium of Bronstein- Semendjajew (Part II, Chapter IV, Para B, Subpara 7).

Conversion Table for Meters, Feet, and Fathoms

Meters	Feet	Fathoms	Meters	Feet	Fathoms	Feet	Meters	Feet	Meters	Fathoms	Meters	Fathoms	Meters
1	3.28	0.55	61	200.13	33.36	1	0.30	61	18.59	1	1.83	61	111.56
2	6.56	1.09	62	203.41	33.90	2	0.61	62	18.90	2	3.66	62	113.39
3	9.84	1.64	63	206.69	34.45	3	0.91	63	19.20	3	5.49	63	115.21
4	13.12	2.19	64	209.97	35.00	4	1.22	64	19.51	4	7.32	64	117.04
5	16.40	2.73	65	213.25	35.54	5	1.52	65	19.81	5	9.14	65	118.87
6	19.69	3.28	66	216.54	36.09	6	1.83	66	20.12	6	10.97	66	120.70
7	22.97	3.83	67	219.82	36.64	7	2.13	67	20.42	7	12.80	67	122.53
8	26.25	4.37	68	223.10	37.18	8	2.44	68	20.73	8	14.63	68	124.36
9	29.53	4.92	69	226.38	37.73	9	2.74	69	21.03	9	16.46	69	126.19
10	32.81	5.47	70	229.66	38.28	10	3.05	70	21.34	10	18.29	70	128.02
11	36.09	6.01	71	232.94	38.82	11	3.35	71	21.64	11	20.12	71	129.84
12	39.37	6.56	72	236.22	39.37	12	3.66	72	21.95	12	21.95	72	131.67
13	42.65	7.11	73	239.50	39.92	13	3.96	73	22.25	13	23.77	73	133.50
14	45.93	7.66	74	242.78	40.46	14	4.27	74	22.56	14	25.60	74	135.33
15	49.21	8.20	75	246.06	41.01	15	4.57	75	22.86	15	27.43	75	137.16
16	52.49	8.75	76	249.34	41.56	16	4.88	76	23.16	16	29.26	76	138.99
17	55.77	9.30	77	252.62	42.10	17	5.18	77	23.47	17	31.09	77	140.82
18	59.06	9.84	78	255.91	42.65	18	5.49	78	23.77	18	32.92	78	142.65
19	62.34	10.39	79	259.19	43.20	19	5.79	79	24.08	19	34.75	79	144.48
20	65.62	10.94	80	262.47	43.74	20	6.10	80	24.38	20	36.58	80	146.30
21	68.90	11.48	81	265.75	44.29	21	6.40	81	24.69	21	38.40	81	148.13
22	72.18	12.03	82	269.03	44.84	22	6.71	82	24.99	22	40.23	82	149.96
23	75.46	12.58	83	272.31	45.38	23	7.01	83	25.30	23	42.06	83	151.79
24	78.74	13.12	84	275.59	45.93	24	7.32	84	25.60	24	43.89	84	153.62
25	82.02	13.67	85	278.87	46.48	25	7.62	85	25.91	25	45.72	85	155.45
26	85.30	14.22	86	282.15	47.03	26	7.92	86	26.21	26	47.55	86	157.28
27	88.58	14.76	87	285.43	47.57	27	8.23	87	26.52	27	49.38	87	159.11
28	91.86	15.31	88	288.71	48.12	28	8.53	88	26.82	28	51.21	88	160.93
29	95.14	15.86	89	291.99	48.67	29	8.84	89	27.13	29	53.04	89	162.76
30	98.43	16.40	90	295.28	49.21	30	9.14	90	27.43	30	54.86	90	164.59
31	101.71	16.95	91	298.56	49.76	31	9.45	91	27.74	31	56.69	91	166.42
32	104.99	17.50	92	301.84	50.31	32	9.75	92	28.04	32	58.52	92	168.25
33	108.27	18.04	93	305.12	50.85	33	10.06	93	28.35	33	60.35	93	170.08
34	111.55	18.59	94	308.40	51.40	34	10.36	94	28.65	34	62.18	94	171.91
35	114.83	19.14	95	311.68	51.95	35	10.67	95	28.96	35	64.01	95	173.74
36	118.11	19.69	96	314.96	52.49	36	10.97	96	29.26	36	65.84	96	175.56
37	121.39	20.23	97	318.24	53.04	37	11.28	97	29.57	37	67.67	97	177.39
38	124.67	20.78	98	321.52	53.59	38	11.58	98	29.87	38	69.49	98	179.22
39	127.95	21.33	99	324.80	54.13	39	11.89	99	30.18	39	71.32	99	181.05
40	131.23	21.87	100	328.08	54.68	40	12.19	100	30.48	40	73.15	100	182.88
41	134.51	22.42	101	331.36	55.23	41	12.50	101	30.78	41	74.98	101	184.71
42	137.80	22.97	102	334.65	55.77	42	12.80	102	31.09	42	76.81	102	186.54
43	141.08	23.51	103	337.93	56.32	43	13.11	103	31.39	43	78.64	103	188.37
44	144.36	24.06	104	341.21	56.87	44	13.41	104	31.70	44	80.47	104	190.20
45	147.64	24.61	105	344.49	57.41	45	13.72	105	32.00	45	82.30	105	192.02
46	150.92	25.15	106	347.77	57.96	46	14.02	106	32.31	46	84.12	106	193.85
47	154.20	25.70	107	351.05	58.51	47	14.33	107	32.61	47	85.95	107	195.68
48	157.48	26.25	108	354.33	59.06	48	14.63	108	32.92	48	87.78	108	197.51
49	160.76	26.79	109	357.61	59.60	49	14.94	109	33.22	49	89.61	109	199.34
50	164.04	27.34	110	360.89	60.15	50	15.24	110	33.53	50	91.44	110	201.17
51	167.32	27.89	111	364.17	60.70	51	15.54	111	33.83	51	93.27	111	203.00
52	170.60	28.43	112	367.45	61.24	52	15.85	112	34.14	52	95.10	112	204.83
53	173.88	28.98	113	370.73	61.79	53	16.15	113	34.44	53	96.93	113	206.65
54	177.17	29.53	114	374.02	62.34	54	16.46	114	34.75	54	98.76	114	208.48
55	180.45	30.07	115	377.30	62.88	55	16.76	115	35.05	55	100.58	115	210.31
56	183.73	30.62	116	380.58	63.43	56	17.07	116	35.36	56	102.41	116	212.14
57	187.01	31.17	117	383.86	63.98	57	17.37	117	35.66	57	104.24	117	213.97
58	190.29	31.71	118	387.14	64.52	58	17.68	118	35.97	58	106.07	118	215.80
59	193.57	32.26	119	390.42	65.07	59	17.98	119	36.27	59	107.90	119	217.63
60	196.85	32.81	120	393.70	65.62	60	18.29	120	36.58	60	109.73	120	219.46

PART 6

(Maritime safety and communications)

Chapter 1

(Safety of life at sea)

6110 International convention for the Safety Of Life At Sea (SOLAS)

The SOLAS Convention of the International Maritime Organisation (**IMO**) of the United Nations in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was adopted in 1914, in response to the Titanic disaster, the second in 1929, the third in 1948 and the fourth in 1960. The 1960 Convention - which was adopted on June 17^{th} 1960 and entered into force on May 26^{th} 1965 - was the first major task for IMO after the Organisation's creation and it represented a considerable step forward in modernising regulations and in keeping pace with technical developments in the shipping industry.

The intention was to keep the convention up to date by periodic amendments but in practice the amendments procedure proved to be very slow. It became clear that it would be impossible to secure the entry into force of amendments within a reasonable period of time.

As a result, a completely new convention was adopted in 1974 which included not only the amendments agreed up until that date but a new amendment procedure - the tacit acceptance procedure - designed to ensure that changes could be made within a specified (and acceptably short) period of time.

Instead of requiring that an amendment shall enter into force after being accepted by e.g. two thirds of the Parties, the tacit acceptance procedure provides that an amendment shall enter into force on a specified date unless, before that date, objections to the amendment are received from an agreed number of parties.

As a result the 1974 convention has been updated and amended on numerous occasions. The convention in force today is sometimes referred to as SOLAS, 1974, as amended.

One important act intended to improve communication in distress cases is the communication act as laid down in chapter IV.

6120 Fundamentals of the Global Maritime Distress and Safety System (GMDSS)

The Global Maritime Distress and Safety System (**GMDSS**) is an automated ship to shore distress alerting system that relies on satellite and advanced terrestrial communications links. The system also provides some limited ship to ship communication capabilities.

Every ship subject to the communication act or the international convention for the Safety Of Life At Sea (**SOLAS**) as defined in 1974 and amended in 1988 must comply with GMDSS. These vessels include:

- All passenger ships regardless of size
- Cargo ships of 300 gross tons and upward.

GMDSS is a system based on linking of Search And Rescue (**SAR**) authorities ashore with shipping in the immediate vicinity of the vessel in distress or in need of assistance. The primary purpose of GMDSS is to automate and improve emergency communications for the world´s shipping industry. GMDSS uses a number of frequencies, modes and systems to accomplish this mission. It uses both, satellite and terrestrial radio systems because each system has its own individual limitations with respect to geographical coverage and services it can provide.

The basic concept of GMDSS is to alert SAR authorities ashore and vessels in the vicinity of a distress so they can assist in a coordinated search and rescue operation with minimum delay.

Under SOLAS, every ship, while at sea, must have the facilities for essential communications, namely:

- Transmitting ship-to-shore distress alerts by at least two separate and independent means;
- Receiving shore-to-ship distress alerts;
- Transmitting and receiving ship-to-ship distress alerts;
- Transmitting and receiving search and rescue co-ordinating communications;
- Transmitting and receiving on-scene communications
- Transmitting and (as required) receiving signals for locating;
- Transmitting and automatically receiving Maritime Safety Information (**MSI**);
- Transmitting and receiving general radio communications to and from shore-based radio systems or networks; and
- Transmitting and receiving bridge-to-bridge communications.

6121 Operating areas

Specific equipment requirements for ships vary according to the sea area (or areas) in which the ship operates. The GMDSS combines various subsystems - which all have different limitations with respect to coverage - into one overall system, and the oceans are divided into four sea areas (Ref. Figure 6121):

- Area A1. Within range of VHF coast stations with continuous Digital Selecting Calling (**DSC**) alerting available (about 20-30 miles)
- Area A2. Beyond area Al, but within range of MF coastal stations with continuous DSC alerting available (about l00 miles)
- Area A3. Beyond the first two areas, but within coverage of geostationary maritime communication satellites (in practice this means Inmarsat). This covers the area between roughly 70 deg N and 70 deg S.
- Area A4. The remaining sea areas. The most important of these is the sea around the North Pole (the area around the South Pole is mostly land). Geostationary satellites, which are positioned above the equator, cannot reach this far.

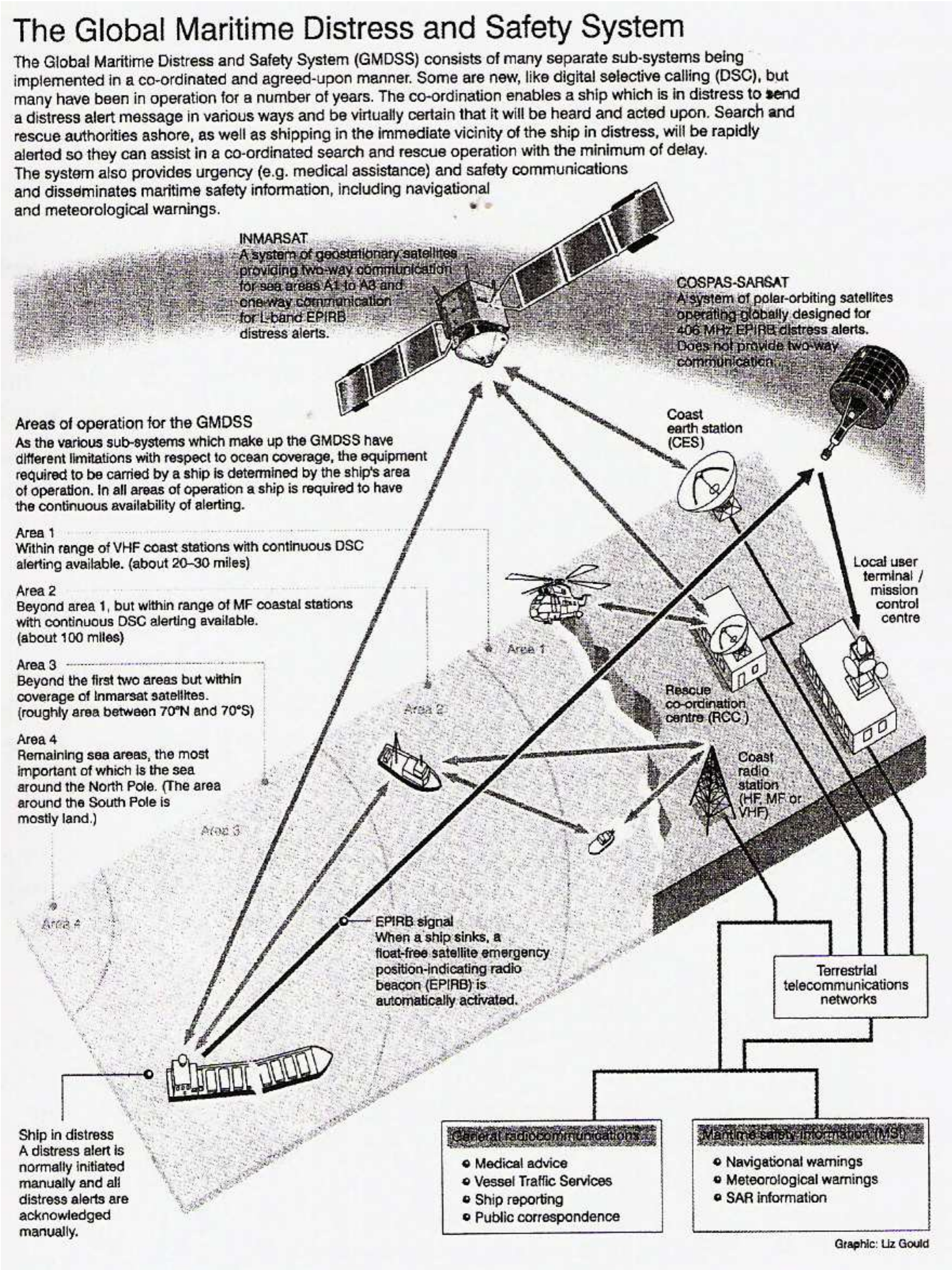


Figure 6121 General concept of GMDSS

Coastal vessels, for example, only have to carry minimal equipment if they do not operate beyond the range of shore-based VHF radio stations, but they may carry satellite equipment. However, some coasts do not have shore-based facilities, so although the ship is close to shore, the area counts as Area A2 or A3. Ships which do go beyond Sea Area A1 have to carry MF equipment as well as VHF - or Inmarsat satellite equipment. Ships which operate beyond MF range have to carry Inmarsat satellite equipment in addition to VHF and MF. Ships which operate in area A4 have to carry HF, MF and VHF equipment.

Most fishers and recreational boaters are already carrying VHF marine radios; however, they are not generally DSC compatible.

At the moment, most fishing vessels and recreational boaters are not required to participate in the GMDSS. But they will find many of the services available useful and may want to acquire equipment which must be registered with the appropriate authorities. Small vessels are also recommended to fit DSC equipment, since once the GMDSS is fully implemented, vessels without DSC will have difficulty contacting ships which are monitoring the DSC calling channel only. However, in a vessel traffic service zones, ships will still be required to maintain a listening watch on the appropriate frequency.

6122 Search And Rescue (SAR) organisations

SAR organisations with their associated stations are considered as an important part of GMDSS. They are consisting of Rescue Coordination Centre´s (RCC), or Maritime Rescue Coordination Centre’s (MRCC). In case a RCC or MRCC is not in the possession of a coast radio station, than it is obliged to continuously monitor DSC channel 70.

Additionally said RCC´s or MRCC´s can communicate with the Network Control Station (**NCS**) and the Coast Earth Station (**CES**) of the organisation operating Inmarsat, as well as with the Local User Terminal (**LUT**) and the Mission Control Centre (**MCC**) of the COSPAS-SARSAT organisation.

6130 The Inmarsat system

The International Mobile Satellite Organisation, previously the **In**ternational **Mar**itime **Sat**ellite (Inmarsat) Organisation, was established by IMO in 1976 to operate satellite maritime communication systems and has become a privately owned company, while retaining its public sector obligations to the maritime distress and safety system.

Inmarsat is a key player within GMDSS, over 75 international partners providing maritime safety communications for ships at sea. Inmarsat provides the space segment necessary for improving distress communications, efficiency and management of ships, as well as public correspondence services.

The Inmarsat system relies on four operational geostationary satellites and their associated **C**ost **E**arth **S**tation’s **(CES)** providing full coverage of the earth between 76° N and 76° S latitudes. Satellite coverage (Figure 6130) is divided into four overlapping regions:

1. Atlantic Ocean - East (AOR-E)
2. Atlantic Ocean - West (AOR-W)
3. Pacific Ocean (POR)
4. Indian Ocean (IOR)

Inmarsat-A, the original Inmarsat system, operates at a transfer rate of up to 64k bits per second and is telephone, telex and facsimile (fax) capable. The similarly sized **Inmarsat-B** system uses digital technology, also at rates to 64kbps. Fleet 77 service is also digital and operates at up to 64kbps.

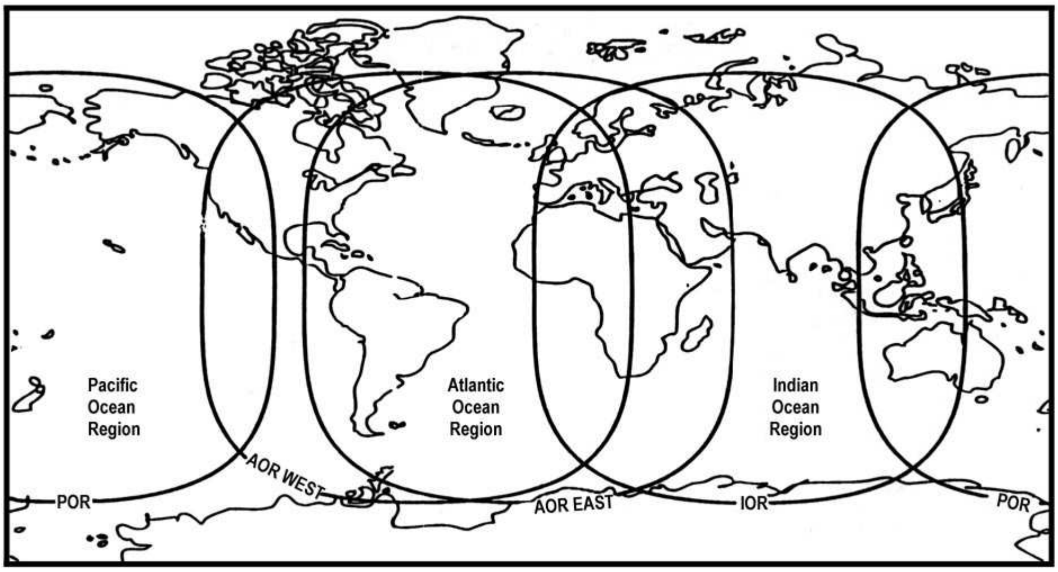


Figure 6130 The four regions of Inmarsat coverage

Inmarsat-C provides a store and forward data messaging capability (but no voice) at 600 bits per second and was designed specifically to meet the GMDSS requirements for receiving **M**aritime **S**afety **I**nformation (**MSI**) data on board ship. These units are small, lightweight and use an Omni-directional antenna.

6140 NAVTEX

NAVTEX is a maritime radio warning system consisting of a series of coast stations transmitting radio teletype safety messages on the internationally standard medium frequency of 518 kHz.

It is a GMDSS requirement for the reception of MSI in coastal and local waters. Coast stations located in 16 see warning areas the so called **NAVAREAS I to XVI** (Ref. Figure 6140) transmit during previously arranged time slots to minimise mutual interference. Routine messages are normally broadcast four times daily. Urgent messages are broadcast upon receipt, provided that an adjacent station is not transmitting. Since the broadcast uses the medium frequency band, a typical station service radius ranges from 100 to 500 NM day and night. Interference from or receipt of stations further away occasionally occurs at night.

Each NAVTEX message broadcast contains a four character header describing: identification of station (first character), message content or type (second character), and message serial number (third and fourth characters). This header allows the microprocessor in the shipboard receiver to screen messages from only those stations relevant to the user, messages of subject categories needed by the user and messages not previously received by the user. Messages so screened are indicated / printed as they are received, to be read by the mariner when convenient. All other messages are suppressed. Suppression of unwanted messages is becoming more and more a necessity to the mariner as the number of messages, including rebroadcast messages, increases yearly.

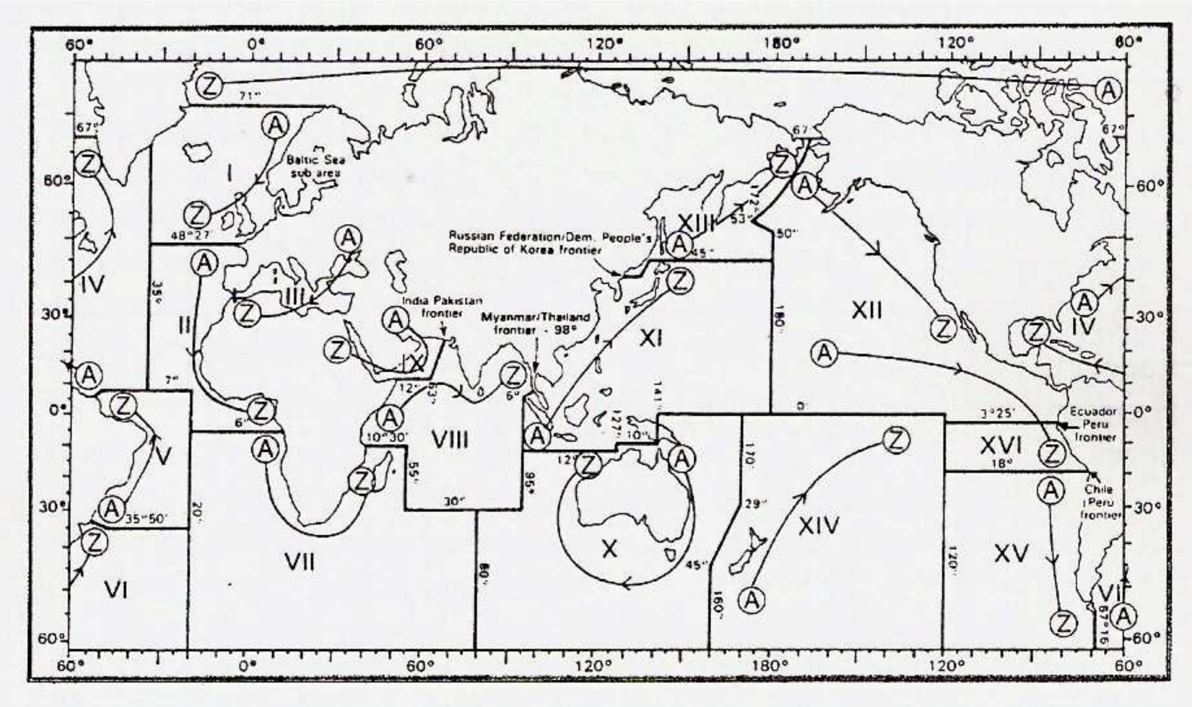


Figure 6140 NAVAREAS of the world wide navigational warning service

With NAVTEX, a mariner will not find it necessary to listen to, or sift through, a large number of non-relevant data to obtain the information necessary for safe navigation.

6150 Digital Selective Calling (DSC)

The digital selective calling is a system of digitalized radio communications which allows messages to be targeted to all stations or to specific stations, allows for unattended and automated receipt and storage of messages for later retrieval, and permits the printing of messages in hardcopy form. All DCS calls automatically include error checking signals and the identity of the calling unit.

Digital codes allow DSC stations to transmit and receive distress messages, transmit and receive acknowledgments of distress messages, relay distress messages, make urgent and safety calls, and initiate routine message traffic.

Each unit has a MAYDAY button which allows the instant transmittal of a distress message to all nearby ships and shore stations. The location of the distress will be automatically indicated if the unit is connected to a GPS or Loran C receiver. Each unit must be registered with the Coast Guard and have unique identifier programmed into it.

Listening watch on 2182 kHz ended with implementation of GMDSS in 1999. When DSC has been implemented worldwide, the traditional listening watch on Channel 16 VHF will no longer be necessary. The introduction of DSC throughout the world is expected to take a number of years.

DSC frequencies are found in the VHF, MF and HF bands. Within each band except VHF, one frequency is allocated for distress, urgent, and safety messages. Other frequencies are reserved for routine calls. In the VHF band, only one channel is available, Channel 70 (156.525 MHz), which is used for all calls. In the MF band, 2187.5 kHz and 2189.5 kHz are reserved for distress /safety, and 2177 kHz for ship to ship and ship to shore calls.

There are four categories of DSC calls:

- **Distress**
- **Urgent**
- **Safety**
- **Routine**

Distress calls are immediately received by rescue authorities for action and all vessels receiving a distress call are alerted by an audible signal.

Each DSC unit has a unique **M**aritime **M**obile **S**ervice **I**dentity **(MMSI)** code number, which is attached to all outgoing messages. The MMSI number is a nine-digit number to identify individual vessels, groups of vessels, and coast stations.

- Ship stations will have a leading number consisting of 3 digits which identify the country in which the ship is registered and is called the **M**aritime **I**dentification **D**igit **(MID)**, followed by 6 digits identifying the vessel.
- A group of vessels will have a leading zero, followed by a unique number for that group consisting of the MID followed by 5 digits identifying the group.
- A coast station will have 2 leading zeros followed by unique number for that station or groups of stations consisting of the MID followed by 4 digits identifying the station or the group of stations.

6160 Radio safety equipment

According to SOLAS the following equipment is recognized as Radio safety equipment:

- **E**mergency **P**osition **I**ndicating **R**adio **B**eacon **(EPIRB)**
- **S**earch **A**nd **R**escue Radar **T**ransponder **(SART)**
- **VHF** handheld equipment

6161 Emergency Position Indicating Radio Beacon (EPIRB)

Two different systems are used for alerting SAR organisations by means of Emergency Position Indicating Radio Beacons (EPIRB). They are the Inmarsat E and the COSPAS-SARSAT systems.

Inmarsat E: The Inmarsat EPIRB is equipped with a GPS receiver and has therefore the ability to provide in an emergency situation within a few minutes high accuracy information concerning its geographic position. Together with the position EPIRB is transmitting information enabling the identification of the vessel (Inmarsat System Code). The total information package is transmitted via a geostationary satellite and the associated CES to the Inmarsat **N**etwork **C**ontrol **S**tation **(NCS)** which alerts the RCC or MRCC nearest to the vessel requiring assistance. Because of the restricted earth coverage of the satellites, reliable operation of the system is possible only in the Areas A1, A2 and A3. The maximum delay from the transmission of the distress information up to the time the RCC or MRCC receives the message is not greater than two minutes. The accuracy of the transmitted position information is better than 100 m.

COSPAS-SARSAT: COSPAS is a Russian acronym for "Space System for Search of Distressed Vessels"; SARSAT signifies "Search and Rescue Satellite Aided Tracking". COSPAS-SARSAT is an international satellite-based search and rescue system, established by Canada, France, the U.S.A. and Russia. These four countries jointly helped develop a 406 MHz satellite emergency position indicating radio beacon (EPIRB), an element of the GMDSS designed to operate with COSPAS-SARSAT system. These automatic-activating EPIRB´s are designed to transmit to a RCC or MRCC a vessel identification and an accurate location of the vessel from anywhere in the world. Additionally the 121,5 MHz international emergency frequency is transmitted to enable SAR Aircraft to locate the area of distress. If an EPIRB is activated, the geostationary Pole orbiting satellites of the COSPAS-SARSAT system pick up the signal, and pass this information together with the EPIRB signal transport delay to a **L**ocal **U**ser **T**erminal **(LUT)**. The LUT calculates from the EPIRB signal transport delay the location of the EPIRB and transmits the total distress information via the **M**ission **C**ontrol **C**entre **(MCC)** to the RCC or MRCC. Due to the low polar orbit there may be a delay in receiving the distress message between 15 minutes and up to some hours. The accuracy of the location of the EPIRB varies between 10 and 50 Nm.

6162 Search and Rescue Radar Transponders (SART´s)

The GMDSS installation on ships include one or more search and rescue radar transponders, devices which are used to locate survival craft or distressed vessels by creating a series of dots on a rescuing ship's 3 cm radar display. The detection range between these devices and ships,

dependent upon the height of the ship's radar mast and the height of the SART, is normally less than ten miles.
The SART is a passive rescue device which, when it senses the pulse from a radar operating in the 9 GHz frequency band, emits a series of pulses in response, which alerts the radar operator that some sort of maritime distress is in progress. Further, the SART signal allows the radar operator to home in on the exact location of the SART. The SART can be activated manually or will activate automatically when placed in water.

The SART signal appears on the radar screen as a series of 12 blips, each 0,64 nautical miles apart. As the vessel or aircraft operating the radar approaches the SART location, the blips change to concentric arcs and within about a mile of the SART become concentric circles, centred on the SART (Ref. Figure 6162).

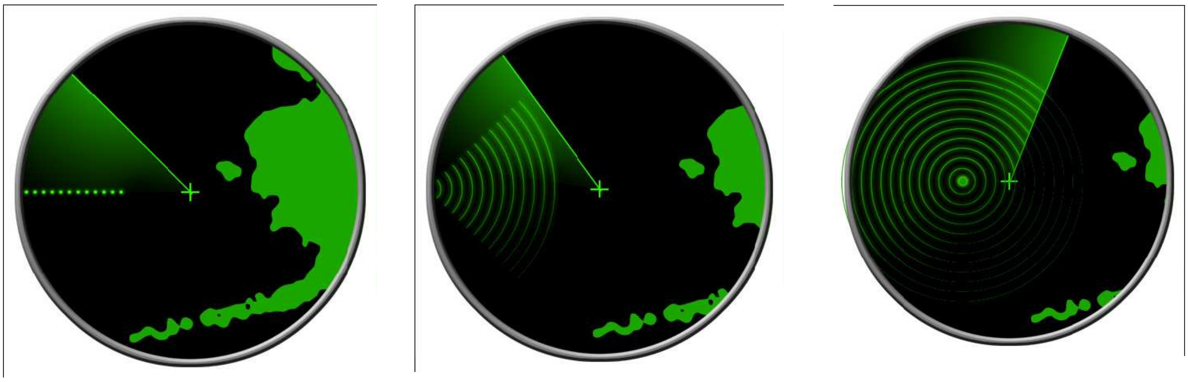


Figure 6162 SART signals at various distances from the transponder

Because the SART actively responds to radar pulses, it also informs its user, with an audible or visual signal, that it is being triggered. This alerts the user in distress that there is an operating radar in the vicinity, whereupon they may send up flares or initiate other actions to indicate their position.

6163 VHF handheld equipment

In case of distress and if the crew is forced to abandon the vessel prior to the arrival of assistance, the crew will have to use handheld VHF equipment to communicate with the rescue ships. Said VHF´s must be able to communicate on channel 16 plus an additional channel as a minimum. However according to an IMO recommendation such equipment shall contain the channels 16, 06, 13, 15 and 17, they shall be GMDSS compatible and water proofed.

6170 Automatic Identification System (AIS)

The Automatic Identification System (**AIS**) is a short range coastal tracking system used on ships and by Vessel Traffic Services (**VTS**) for identifying and locating vessels by electronically exchanging data with other nearby ships and VTS stations. Information such as unique identification, position, course, and speed can be displayed on a screen or an ECDIS. AIS is intended to assist the vessel's watch standing officers and allow maritime authorities to track and monitor vessel movements.

The International Maritime Organization's (**IMO**) International Convention for the Safety of Life at Sea (**SOLAS**) requires AIS to be fitted aboard international voyaging ships with gross tonnage of 300 or more tons, and all passenger ships regardless of size.

6171 Applications and limitations

AIS is used in navigation primarily for collision avoidance. Due to the limitations of VHF radio communications, and because not all vessels are equipped with AIS, the system is meant to be used primarily as a means of lookout and to determine risk of collision rather than as an automated collision avoidance system, in accordance with the International Regulations for Preventing Collisions at Sea (**COLREGS**) described in Chapter 6 part 2 below.

When a ship is navigating at sea, the movement and identity of other ships in the vicinity is critical for navigators to make decisions to avoid collision with other ships and dangers (shoal or rocks). Visual observation (unaided, binoculars, night vision), audio exchanges (whistle, horns, VHF radio), and radar or Automatic Radar Plotting Aid (ARPA) are historically used for this purpose. However, a lack of positive identification of the targets on the displays, and time delays and other limitation of radar for observing and calculating the action and response of ships around, especially on busy waters, sometimes prevent possible action in time to avoid collision.

While requirements of AIS are only to display very basic text information, the data obtained can be integrated with a graphical electronic chart or a radar display, providing consolidated navigational information on a single display.

The system coverage range is similar to other VHF applications, essentially depending on the height of the antenna. Its propagation is better than that of radar, due to the longer wavelength, so it’s possible to “see” around bends and behind islands if the land masses are not too high. A typical value to be expected at sea is nominally 20 nautical miles.

6172 Basic overview

AIS transponders automatically broadcast information, such as their position, speed, and navigational status, at regular intervals via a VHF transmitter built into the transponder. The information originates from the ship's navigational sensors. Other information, such as the vessel name and VHF MMSI, is programmed when installing the equipment and is also transmitted regularly. The signals are received by AIS transponders fitted on other ships or on land based systems, such as VTS systems. The received information can be displayed on a screen or chart plotter, showing the other vessels' positions in much the same manner as a radar display.

The AIS standard describes two major classes of AIS units:

- Class A - mandated for use on SOLAS Chapter V vessels.
- Class B - a low power, lower cost derivative for leisure and non-SOLAS markets.

61721 Class A units

The AIS transponder normally works in an autonomous and continuous mode. Transmissions are found on two frequencies, VHF maritime channels 87B (161.975 MHz) and 88B (162.025 MHz). Although only one radio channel is necessary, each station transmits and receives over two radio channels to avoid interference problems, and to allow channels to be shifted without communications loss from other ships. The system provides for automatic contention resolution between itself and other stations, and communications integrity is maintained even in overload situations.

In order to ensure that the VHF transmissions of different transponders do not occur at the same time the signals are time multiplexed using a technology called Self-Organized Time Division Multiple Access (**STDMA**). In order to make the most efficient use of the bandwidth available, vessels which are anchored or are moving slowly transmit less frequently than those that are moving faster or are maneuvering.

Each station determines its own transmission schedule (slot), based upon data link traffic history and knowledge of future actions by other stations. A position report from one AIS station fits into one of 2250 time slots established every 60 seconds on each frequency. AIS stations continuously synchronize themselves to each other, to avoid overlap of slot transmissions. When a station changes its slot assignment, it announces both the new location and the timeout for that location. In this way new stations, including those stations which suddenly come within radio range close to other vessels will always be received by those vessels.

The STDMA broadcast mode allows the system to be overloaded by 400 to 500% through sharing of slots, and still provide nearly 100% throughput for ships closer than 8 to 10 NM to each other in a ship to ship mode. In the event of system overload, only targets further away will be subject to drop-out, in order to give preference to nearer targets that are a primary concern to ship operators. In practice, the capacity of the system is nearly unlimited, allowing for a great number of ships to be accommodated at the same time.

AIS transceiver sends the following data every 2 to 10 seconds depending on vessels speed while underway, and every 3 minutes while vessel is at anchor. This data includes:

- The vessel's Maritime Mobile Service Identity (MMSI) - a unique nine digit identification number.
- Navigation status - "at anchor", "under way using engine(s)", "not under command", etc
- Rate of turn - right or left, 0 to 720 degrees per minute
- Speed over ground - 0.1-knot (0.19 km/h) resolution from 0 to 102 knots (189 km/h)
- Position accuracy:
- Longitude - to 1/10000 minute
- Latitude - to 1/10000 minute
- Course over ground - relative to true north to 0.1 degree
- True Heading - 0 to 359 degrees from e.g. gyro compass
- Time stamp - UTC time accurate to nearest second when this data was generated

In addition, the following data is broadcast every 6 minutes:

- IMO ship identification number - a seven digit number that remains unchanged upon transfer of the ship's registration to another country
- Radio call sign - international radio call sign, up to seven characters, assigned to the vessel by its country of registry

- Name - 20 characters to represent the name of the vessel
- Type of ship/cargo
- Dimensions of ship - to nearest meter
- Location of positioning system's (e.g. GPS) antenna onboard the vessel
- Type of positioning system - such as GPS, DGPS or LORAN-C
- Draught of ship - 0.1 meter to 25.5 meters
- Destination - max 20 characters
- ETA (estimated time of arrival) at destination - UTC month/date hour minute

61722 Class B units

Class B AIS is a "polite", listen-before-transmitting system that will transmit on the first available slot. A position report from one AIS station fits into one of 2250 time slots established every 60 seconds.

Ship borne mobile equipment provides facilities not necessarily in full accord with IMO AIS carriage requirements. The Class B is nearly identical to the Class A, except the Class B:

- Has a reporting rate less than a Class A (e.g. every 30 sec. when under 14 knots, as opposed to every 10 sec. for Class A)
- Does not transmit the vessel’s IMO number
- Does not transmit ETA or destination
- Does not transmit navigational status
- Is only required to receive, not transmit, text safety messages
- Is only required to receive, not transmit, application identifiers (binary messages)
- Does not transmit rate of turn information
- Does not transmit maximum present static draught

61723 Passive use of AIS

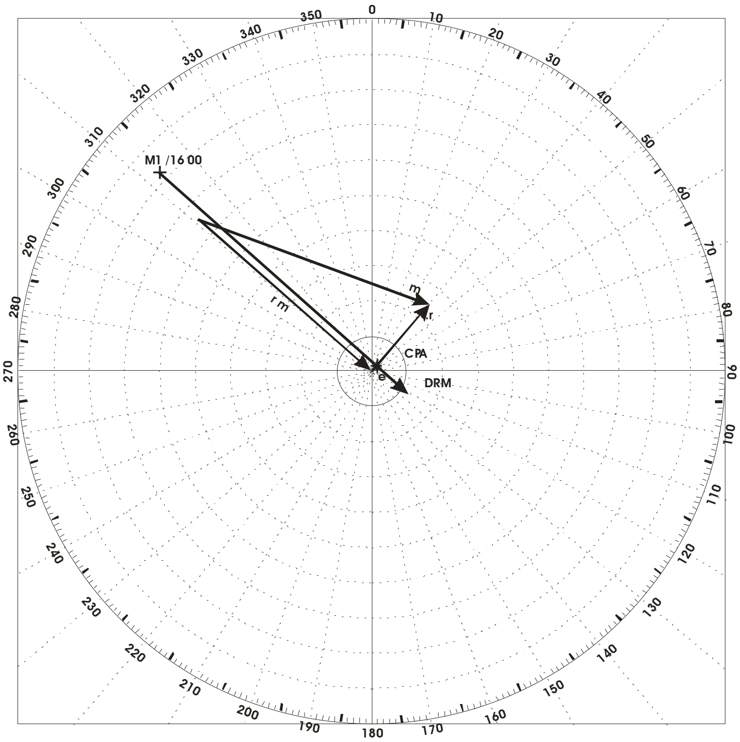
Small NON SOLAS vessels may use AIS data obtained from chip AIS receivers in order to get information about the MMSI, the geographic position, the course and the speed over ground off other vessels in their vicinity. Said information can be displayed in Stand alone AIS equipment, in chart plotters, or in laptops and so provide to the watch keepers’ vital information for collision avoidance actions to be taken.

6173 Examples

61731 Closest Point of Approach (CPA)

Situation: *Sailing vessel (R) is sailing a true course COG = 040° at a speed of SOG = 5 Kn. At 16 00 local time in position 37° 30´N and 023° 45´E, observes in the AIS screen at a range of 8,2 Sm a target (M) being in position 37° 36´N and 023° 38´E and moving at a speed of SOG = 14 Kn towards 110° true.*

Required: *(1) Direction (DRM) and speed of Relative Movement (SRM) assuming both vessels maintain their speed and course.*
(2) Bearing and range at Closest Point of Approach (CPA).
(3) Estimated time of Arrival at CPA.



Solution: *(1) Due to the fact the latitude of M is greater then the latitude of R and its longitude is smaller then that from R, the position of M is some where north westward from R. From the difference in latitude (37° 36´-37° 30´=6 Sm) and the range at 16 00 (8,2 Sm), calculate the true bearing of (M): 360°-arcsin (6/8,2) = 313°. Plot and label the relative position M1 at 16 00 (8,2 Sm / 313°) using for distances the scale factor 1:1 Draw the reference ship vector er corresponding to the course and speed of R (5 Kn / 40°) using for speeds the scale factor 2:1. Draw the vector em corresponding to the course and speed of M (14 Kn / 110°). The third side of the triangle, rm, is the vector defining the direction (DRM) and the speed (SRM) of the relative movement (131° / 13,2 Kn).*

(2) Move the relative movement vector rm parallel up to M1 and draw from the origin of R a perpendicular to it. The distance and the direction of the vector from the origin of R to the relative movement vector is the Closest point of approach (CPA = 1,1 Sm / 41°) .

(3) Measure M1 to CPA: 8,1 Sm. With this MRM and SRM (8,1 Sm/12,6 Kn) obtain time interval to CPA at 38,5 min. ETA at CPA= 16 00 + 38,5 = 16 39.

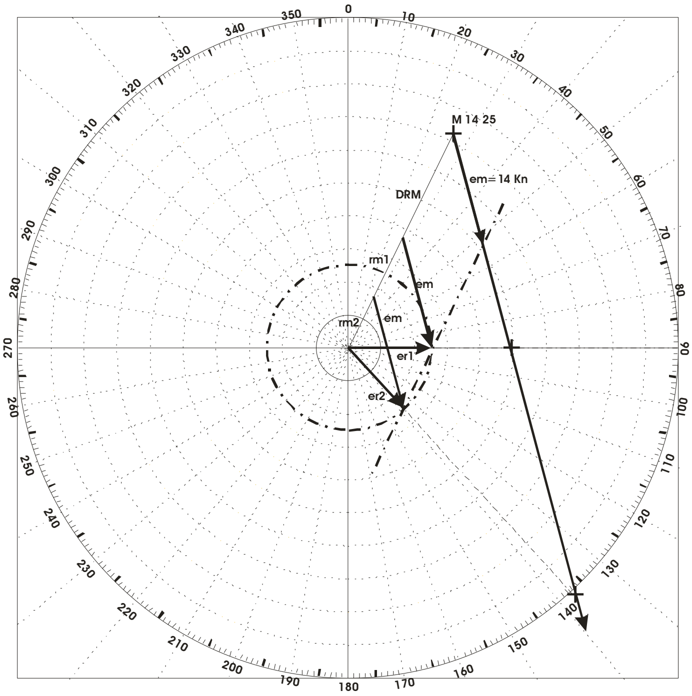
Answer: *(1) DRM 131° SRM 13,2 Kn*
(2) CPA 41° 1,1 Sm.
(3) ETA at CPA 16 39.

61732 Interception

Situation: *Own vessel (R) in position 37° 25´N and 023° 40´E observes at 14 25 local time in the AIS screen at a range of 14,5 Sm a target (M) being in position 37° 38´N and 023° 48,1´E and moving at a speed of SOG = 14 Kn towards 165° true. The maximum speed of the own ship is 10 Kn.*

Required: *(1) The COG to be steered to intercept (M).*
(2) Estimated time of interception.
(3) The geographical position of the point of interception.

Solution: *(1) Due to the fact the latitude as well the longitude of (M) are greater then those from R, the position of (M) is some where north eastward from (R).*



From the difference in latitude (37° 38´-37° 25´=13 Sm) and the range at 14 25 (14,5 Sm), calculate the true bearing of (M): 90°-arcsin (13/14,5) = 26°. Plot and label the relative position (M) at 14 25 (14,5 Sm / 26°) using for distances the scale factor 2:1. At the origin of (R) draw a circle with a diameter corresponding to the reference ship vector (er=10 Kn) using for speeds the scale factor 4:1. The line from the origin from (R) to the position of (M) defines the direction of the relative movement of two vessels being at collision course (CPA=0 Sm). Draw the vector em corresponding to the course and speed of M (14 Kn / 165°). Move em towards the origin of (R) as often as it meats the reference ship vector circle. The third side of the triangles, created by DRM (rm1 / rm2) and em, are the vectors er1 and er2 defining the courses the own ship shall steer to intercept (M) at a maximum speed of 10 Kn (90° /138°).

(2) Steering a course of 90° (R) will intercept M at a distance of 9,8 Sm from origin i.e. at 15 24 local time. If (R) decides to steer a course of 138°, then it will intercept (M) at a distance of 20,4 Sm from origin i.e. at16 27 local time.

(3) Due to the fact (R) is steering 90° the latitude of (R) remains unchanged whilst it longitude increases by: 9,8 Sm/cos(37,4°) = 12,4´. The geographical position of (R) reads therefore: 37°25´N / 23° 52,4´E. The latitude of (R) at 16 27 decreases by: 20,4 Sm sin(138°-90°) = 15,2´and reads 37° 9,8´N, whilst its longitude increases by: 20,4 Sm * cos(138°-90°) / cos37,3° = 17,2´and reads 23° 57,2´E*

Answer: *(1) (R) can steer two courses to intercept (M), either 90° or 138°*
(2) ETA at course 90°: 15 24 / ETA at course 138° 16 27
(3) 37°25´N / 23° 52,4´E at 15 24 local time and 37° 9,8´N / 23° 57,2´E at 16 27 local time.

PART 6

(Maritime safety and communications)

Chapter 2

(Prevention of collisions at sea)

6210 Adoption / Entry in to force

The IMO convention on the international regulations for preventing collisions at sea (**COLREGs)** has been adopted October the 20th 1972, and its entry into force occurred July the 15th 1977.

The 1972 Convention was designed to update and replace the Collision Regulations of 1960 which were adopted at the same time as the 1960 SOLAS Convention. One of the most important innovations in the 1972 was the recognition given to traffic separation schemes. **Rule 10** gives guidance in determining safe speed, the risk of collision and the conduct of vessels operating in or near traffic separation schemes.

The first such traffic separation scheme was established in the Dover Strait in 1967. It was operated on a voluntary basis at first but in 1971 the IMO Assembly adopted a resolution stating that observance of all traffic separation schemes be made mandatory, and the COLREGs make this obligation clear.

6220 Technical provisions

The COLREGs include 38 rules divided into five sections and four Annexes:

- Part A - General;
- Part B - Steering and Sailing;
- Part C - Lights and Shapes;
- Part D - Sound and Light signals;
- Part E – Exemptions and;
- Four Annexes containing technical requirements concerning
    - lights their shapes and positioning;
    - sound signalling appliances;
    - additional signals for fishing vessels when operating in close proximity and;
    - International distress signals.

6230 Amendments

In the mean time a number of amendments have been incorporated into the COLREGs to consider the needs of specific types of vessels engaged in specific operations, and to clarify some technical aspects. Those amendments are:

- **The 1981 amendment (**in force since June the 1st 1983) covering a number of rule changes. However the most important change concerns rule 10, which has been amend to enable vessels carrying out safety operations, such as dredging or surveying, to carry these functions in traffic separation schemes. The amendments affect several rules, including rule 1(e) classifying the application of the convention to vessels of special construction, Rule 3(h) and 10(c) which defines a vessel constrained by her draught crossing traffic lanes.
- **The 1989 amendment (**in force since April the 19th 1991).The amendment concerns Rule 10 and is designed to stop unnecessary use of the inshore traffic zone
- **The 1993 amendment (**in force since November the 4th 1995) mostly concerned with positioning of lights.
- **The 2001 amendment (**in force since November the 29th 2003) introduced to cover rules relating to Wing-in-Ground (WIG) craft. The following are amended:
  - General Definitions (Rule 3) - to provide the definition of Wing-In-Ground (WIG) craft;
  - Action to avoid collision (Rule 8 (a)) - to make it clear that any action to avoid collision should be taken in accordance with the relevant rules in the COLREGs and to link Rule 8 with the other steering and sailing rules;
  - Responsibilities between vessels (Rule 18) - to include a requirement that a WIG craft, when taking off, landing and in flight near the surface, shall keep clear of all other vessels and avoid impeding their navigation and also that a WIG craft operating on the water surface shall comply with the Rules as for a power-driven vessel;
  - Power-driven vessels underway (Rule 23) - to include a requirement that WIG craft shall, in addition to the lights prescribed in paragraph 23 (a) of the Rule, exhibit a high-intensity all-round flashing red light when taking off, landing and in-flight near the surface;
  - Seaplanes (Rule 31) - to include a provision for WIG craft;
  - Equipment for sound signals and sound signals in restricted visibility (Rules 33 and 35) - to cater for small vessels;
  - Positioning and technical details of lights and shapes (Annex I) - amendments with respect to high-speed craft (relating to the vertical separation of masthead lights); and
  - Technical details of sound signal appliances (Annex III) - amendments with respect to whistles and bell or gong to cater for small vessels.

6240 Rules of the international regulation for preventing collision at sea

Part A – General

Rule1. Application

(As amended by the 1981 amendment)

(a) These Rules shall apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels.
(b) Nothing in these Rules shall interfere in the operation of special rules made by an appropriate authority for roadstead’s, harbours, rivers, lakes or inland waterways

connected with the high seas and navigable by seagoing vessels. Such special rules shall conform as closely as possible to these Rules.

(c) Nothing in these Rules shall interfere with the operation of any special rules made by the Government of any State with respect to additional station or signal lights or shapes or whistle signals for ships of war and vessels proceeding under convoy, or with respect to additional station or signal lights for fishing vessels fishing as a fleet. These additional station or signal lights or whistle signals shall, so far as possible, be such that they cannot be mistaken for any light, shape, or signal authorized elsewhere under these Rules.

(d) Traffic separation schemes may be adopted by the Organization for the purpose of these Rules.

(e) Whenever the Government concerned shall have determined that a vessel of special construction or purpose cannot comply fully with the provisions of any of these Rules with respect to number, position, range or arc of visibility of lights or shapes, as well as to the disposition and characteristics of sound-signalling appliances, such vessel shall comply with such other provisions in regard to number, position, range or arc of visibility of lights or shapes, as well as to the disposition and characteristics of sound-signalling appliances, as her Government shall have determined to be the closest possible compliance with these Rules in respect to that vessel.

Rule2. Responsibility

(a) Nothing in these Rules shall exonerate any vessel, or the owner, master, or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precaution which may be required by the ordinary practice of seamen, or by the special circumstances of the case.

(b) In construing and complying with these Rules due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger.

Rule3. General Definitions

(As amended by the 1981 and 2001 amendments)

For the purpose of these Rules, except where the context otherwise requires:

(a) The word **"vessel"** includes every description of watercraft, including non-displacement craft and seaplanes, used or capable of being used as a means of transportation on water.

(b) The term **"power driven vessel"** means any vessel propelled by machinery.

(c) The term **"sailing vessel"** means any vessel under sail provided that propelling machinery, if fitted, is not being used.

(d) The term **"vessel engaged in fishing"** means any vessel fishing with nets, lines, trawls, or other fishing apparatus which restrict manoeuvrability, but does not include a vessel fishing with trolling lines or other fishing apparatus which do not restrict manageability.

(e) The term **"seaplane"** includes any aircraft designed to manoeuvre on the water.

(f) The term **"vessel not under command"** means a vessel which through some exceptional circumstance is unable to manoeuvre as required by these Rules and is therefore unable to keep out of the way of another vessel.

(g) The term **"vessel restricted in her ability to manoeuvre"** means a vessel which from the nature of her work is restricted in her ability to manoeuvre as required by these Rules and is therefore unable to keep out of the way of another vessel. The term shall include but not be limited to:

- (I) A vessel engaged in laying, servicing, or picking up a navigational mark, submarine cable or pipeline;
- (II) A vessel engaged in dredging, surveying or underwater operations;
- (III) A vessel engaged in replenishment or transferring persons, provisions or cargo while underway;
- (IV) A vessel engaged in the launching or recovery of aircraft;
- (V) A vessel engaged in mine clearance operations;
- (VI) A vessel engaged in a towing operation such as severely restricts the towing vessel and her tow in their ability to deviate from their course.

(h) The term **"vessel constrained by her draft"** means a power driven vessel which because of her draft in relation to the available depth and width of navigable water is severely restricted in her ability to deviate from the course she is following.

(i) The word **"underway"** means a vessel is not at anchor, or made fast to the shore, or aground.

(j) The words **"length"** and **"breadth"** of a vessel mean her length overall and greatest breadth.

(k) Vessels shall be deemed to be in sight of one another only when one can be observed visually from the other.

(l) The term "restricted visibility" means any condition in which visibility is restricted by fog, mist, falling snow, heavy rainstorms, sandstorms and any other similar causes.

(m) The term **"WIG craft"** means a multimodal craft which, in its main operational mode, flies in close operational proximity to the surface by utilising surface-effect action.

Part B - Steering and Sailing Rules

Section I - Conduct of Vessels in any Condition of Visibility

Rule4. Application

Rules in this section apply to any condition of visibility.

Rule5. Look-out

Every vessel shall at all times maintain a proper look-out by sight as well as by hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision.

Rule6. Safe Speed

Every vessel shall at all times proceed at a safe speed so that she can take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions.
In determining a safe speed the following factors shall be among those taken into account:

(a) By all vessels:
- (I) The state of visibility;
- (II) The traffic density including concentrations of fishing vessels or any other vessels;
- (III) The manageability of the vessel with special reference to stopping distance and turning ability in the prevailing conditions;
- (IV) At night the presence of background light such as from shore lights or from back scatter from her own lights;
- (V) The state of wind, sea and current, and the proximity of navigational hazards;
- (VI) The draft in relation to the available depth of water.

(b) Additionally, by vessels with operational radar:
- (I) The characteristics, efficiency and limitations of the radar equipment;
- (II) Any constrains imposed by the radar range scale in use;
- (III) The effect on radar detection of the sea state, weather and other sources of interference;
- (IV) The possibility that small vessels, ice and other floating objects may not be detected by radar at an adequate range;
- (V) The number location and movement of vessels detected by radar;
- (VI) The more exact assessment of the visibility that may be possible when radar is used to determine the range of vessels or other objects in the vicinity.

Rule7. Risk of Collision

(a) Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist.

(b) Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision and radar plotting or equivalent systematic observation of detected objects.

(c) Assumptions shall not be made on the basis of scanty information, especially scanty radar information.

(d) In determining if risk of collision exists the following considerations shall be among those taken into account:

(I) Such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change;

(II) Such risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.

Rule8. Action to Avoid Collision

(As amended by the 2001 amendment)

(a) Any action taken to avoid collision shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship.

(b) Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit be large enough to be readily apparent to another vessel observing visually or by radar. a succession of small alterations of course and/or speed shall be avoided.

(c) If there is sufficient sea room, alteration of course alone may be the most effective action to avoid a close-quarters situation provided that it is made in good time, is substantial and does not result in another close-quarters situation.

(d) Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear.

(e) If necessary to avoid collision or allow more time to asses the situation, a vessel may slacken her speed or take all way off by stopping or reversing her means of propulsion.

(f) (I) A vessel which, by any of these rules, is required not to impede the passage or safe passage of another vessel shall when required by the circumstances of the case, take early action to allow sufficient sea room for the safe passage of the other vessel.

(II) A vessel required not to impede the passage or safe passage of another vessel is not relieved of this obligation if approaching the other vessel so as to involve risk of collision and shall, when taking action, have full regard to the action which may be required by the rules of this part.

(III) A vessel the passage of which is not to be impeded remains fully obliged to comply with the rules of this part when the two vessels are approaching one another so as to involve risk of collision.

Rule9. Narrow Channels

(a) A vessel proceeding along the course of a narrow channel or fairway shall keep as near to the outer limit of the channel or fairway which lies on her starboard side as is safe and practicable.

(b) A vessel of less than 20 meters in length or a sailing vessel shall not impede the passage of a vessel which can safely navigate only within a narrow channel or fairway.

(c) A vessel engaged in fishing shall not impede the passage of any other vessel navigating within a narrow passage or fairway.

(d) A vessel shall not cross a narrow passage or fairway if such crossing impedes the passage of a vessel which can safely navigate only within such channel or fairway. The latter vessel may use the sound signal prescribed in Rule 34(d) if in doubt as to the intention of the crossing vessel.

(e) (I) In a narrow channel or fairway when overtaking can take place only when the vessel to be overtaken has to take action to permit safe passing, the vessel intending to overtake shall indicate her intention by sounding the appropriate signal prescribed in Rule 34(c)(I). The vessel to be overtaken shall, if in agreement, sound the appropriate signal prescribed in Rule 34(c)(II) and take steps to permit safe passing. If in doubt she may sound the signals prescribed in Rule 34(d).

(II) This rule does not relieve the overtaking vessel of her obligation under Rule 13.

(f) A vessel nearing a bend or an area of a narrow channel or fairway where other vessels may be obscured by an intervening obstruction shall navigate with particular alertness and caution and shall sound the appropriate signal prescribed in Rule 34(e).

(g) Any vessel shall, if the circumstances of the case admit, avoid anchoring in a narrow channel.

Rule10. Traffic Separation Schemes

(As amended by the 1981, 1989 and 2001 amendments)

(a) This rule applies to traffic separation schemes adopted by the Organization and does not relieve any vessel of her obligation under any other rule.

(b) A vessel using a traffic separation scheme shall:

(I) Proceed in the appropriate traffic lane in the general direction of traffic flow for that lane.

(II) So far as is practicable keep clear of a traffic separation line or separation zone.

(III) Normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from either side shall do so at as small an angle to the general direction of traffic flow as practicable.

(c) A vessel shall so far as practicable avoid crossing traffic lanes, but if obliged to do so shall cross on a heading as nearly as practicable at right angles to the general direction of traffic flow.

(d) (I) A vessel shall not use an inshore traffic zone when she can safely use the appropriate traffic lane within the adjacent traffic separation scheme. However, vessels of less than 20 meters in length, sailing vessels and vessels engaged in fishing may use the inshore traffic zone.

(II) Notwithstanding subparagraph (d)(I), a vessel may use an inshore traffic Zone when en route to or from a port, offshore installation or structure, pilot station or any other place situated within the inshore traffic zone, or to avoid immediate danger.

(e) A vessel, other than a crossing vessel or a vessel joining or leaving a lane shall not normally enter a separation zone or cross a separation line except:
 (I) In cases of emergency to avoid immediate danger.
 (II) To engage in fishing within a separation zone.

(f) A vessel navigating in areas near the terminations of traffic separation schemes shall do so with particular caution.

(g) A vessel shall so far as practicable avoid anchoring in a traffic separation scheme or in areas near its terminations.

(h) A vessel not using a traffic separating scheme shall avoid it by as wide a margin as is practicable.

(i) A vessel engaged in fishing shall not impede the passage of any vessel following a traffic lane.

(j) A vessel of less than 20 meters in length or a sailing vessel shall not impede the safe passage of a power driven vessel following a traffic lane.

(k) A vessel restricted in her ability to manoeuvre when engaged in an operation for the maintenance of safety of navigation in a traffic separating scheme is exempted from complying with this Rule to the extent necessary to carry out the operation.

(l) A vessel restricted in her ability to manoeuvre when engaged in an operation for the laying, servicing or picking up a submarine cable, within a traffic separating scheme, is exempted from complying with this Rule to the extent necessary to carry out the operation.

Section II - Conduct of Vessels in Sight of One Another

Rule11. Application

Rules in this section apply to vessels in sight of one another.

Rule12. Sailing Vessels

(a) When two sailing vessels are approaching one another, so as to involve risk of collision, one of them shall keep out of the way of the other as follows:
 (I) When each of them has the wind on a different side, the vessel which has the wind on the port side shall keep out of the way of the other.
 (II) When both have the wind on the same side, the vessel which is to windward shall keep out of the way of the vessel which is to leeward.
 (III) If the vessel with the wind on the port side sees a vessel to windward and cannot determine with certainty whether the other vessel has the wind on the port or the starboard side, she shall keep out of the way of the other.

(b) For the purposes of this Rule the windward side shall be deemed to be the side opposite that on which the mainsail is carried or, in the case of a square rigged vessel, the side opposite to that on which the largest fore-and-aft sail is carried.

Rule13. Overtaking

(a) Notwithstanding anything contained in the Rules of Part B, Sections I and II, any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

(b) A vessel shall be deemed to be overtaking when coming up with a another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the stern light of that vessel but neither of her sidelights.

(c) When a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly.

(d) Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear.

Rule14. Head-on Situation

(a) When two power driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights in line or nearly in line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

(c) When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly.

Rule15. Crossing Situation

When two power driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Rule16. Action by Give-way Vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

Rule17. Action by Stand-on Vessel

(a) (I) Where one of two vessels is to keep out of the way of the other shall keep her course and speed.

(II) The latter vessel may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in accordance with these Rules.

(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(II) of this Rule to avoid collision with another power driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

Rule18. Responsibilities between vessels

(As amended by the 2001 amendment)

Except where rules 9, 10, and 13 otherwise require:

(a) A power driven vessel underway shall keep out of the way of:
(I) a vessel not under command;
(II) a vessel restricted in her ability to manoeuvre;
(III) a vessel engaged in fishing;
(IV) a sailing vessel;

(b) A sailing vessel under way shall keep out of the way of:
(I) a vessel not under command;
(II) a vessel restricted in her ability to manoeuvre;
(III) a vessel engaged in fishing;

(c) A vessel engaged in fishing when underway shall, so far as possible, keep out of the way of:
(I) a vessel not under command;
(II) a vessel restricted in her ability to manoeuvre.

(d) (I) Any vessel other than a vessel not under command or a vessel restricted in her ability to manoeuvre shall, if the circumstances of the case admit, avoid impeding the safe passage of a vessel constrained by her draft, exhibiting the signals in Rule 28.

(II) A vessel constrained by her draft shall navigate with particular caution having full regard to her special condition.

(e) A seaplane on the water shall, in general, keep well clear of all vessels and avoid impeding their navigation. In circumstances, however, where risk of collision exists, she shall comply with the Rules of this Part.

(f) (I) A Wig craft shall, when taking off, landing and in flight near the surface, keep well clear of all other vessels and avoid impeding their navigation

(II) A WIG craft operating on the water surface shall comply with the Rules of this Part as if it were a power-driven vessel.

Section III - Conduct of Vessels in Restricted Visibility

Rule19. Conduct of Vessels in Restricted Visibility

(a) This rule applies to vessels not in sight of one another when navigating in or near an area of restricted visibility.

(b) Every vessel shall proceed at a safe speed adapted to the prevailing circumstances and condition of restricted visibility. A power driven vessel shall have her engines ready for immediate maneuver.

(c) Every vessel shall have due regard to the prevailing circumstances and conditions of restricted visibility when complying with the Rules of Section I of this Part.

(d) A vessel which detects by radar alone the presence of another vessel shall determine if a close-quarters situation is developing and/or risk of collision exists. If so, she shall take avoiding action in ample time, provided that when such action consists of an alteration in course, so far as possible the following shall be avoided:

(I) An alteration of course to port for a vessel forward of the beam, other than for a vessel being overtaken;

(II) An alteration of course toward a vessel abeam or abaft the beam.

(e) Except where it has been determined that a risk of collision does not exist, every vessel which hears apparently forward of her beam the fog signal of another vessel, or which cannot avoid a close-quarters situation with another vessel forward of her beam, shall reduce her speed to be the minimum at which she can be kept on her course. She shall if necessary take all her way off and in any event navigate with extreme caution until danger of collision is over.

Part C - Lights and Shapes

Rule20. Application

(a) Rules in this part shall be complied with in all weathers.

(b) The Rules concerning lights shall be complied with from sunset to sunrise, and during such times no other lights shall be exhibited, except such lights which cannot be mistaken for the lights specified in these Rules or do not impair their visibility or distinctive character, or interfere with the keeping of a proper look-out.

(c) The lights prescribed by these rules shall, if carried, also be exhibited from sunrise to sunset in restricted visibility and may be exhibited in all other circumstances when it is deemed necessary.

(d) The Rules concerning shapes shall be complied with by day.

(e) The lights and shapes specified in these Rules shall comply with the provisions of Annex I to these Regulations.

Rule21. Definitions

(a) **"Masthead light"** means a white light placed over the fore and aft centreline of the vessel showing an unbroken light over an arc of horizon of **225 degrees** and so fixed as to show the light from right ahead to **22.5 degrees** abaft the beam on either side of the vessel.

(b) **"Sidelights"** means a green light on the starboard side and a red light on the port side each showing an unbroken light over an arc of horizon of **112.5 degrees** and so fixed as to show the light from right ahead to **22.5 degrees** abaft the beam on the respective side. In a vessel of less than 20 meters in length the sidelights may be combined in one lantern carried on the fore and aft centreline of the vessel.

(c) **"Stern light"**, means a white light placed as nearly as practicable at the stern showing an unbroken light over an arc of horizon of **135 degrees** and so fixed as to show the light **67.5 degrees** from right aft on each side of the vessel.

(d) **"Towing light"** means a yellow light having the same characteristics as the **"stern light"** defined in paragraph (c) of this Rule.

(e) **"All round light"** means a light showing an unbroken light over an arc of horizon of **360 degrees**.

(f) **"Flashing light"** means a light flashing at regular intervals at a frequency of **120 flashes or more per minute**.

Rule22. Visibility of Lights

(As amended by the 1993 amendment)

The lights prescribed in these Rules shall have intensity as specified in Section 8 of Annex I to these Regulations so as to be visible at the following minimum ranges:

(a) In vessels of 50 meters or more in length:
- a masthead light, 6 miles;
- a sidelight, 3 miles;
- a towing light, 3 miles;
- a white red, green or yellow all-around light, 3 miles.

(b) In vessels of 12 meters or more in length but less than 50 meters in length;
- a masthead light, 5 miles; except that where the length of the vessel is less than 20 meters, 3 miles;
- a sidelight, 2 miles;
- a stern light, 2 miles,
- a towing light, 2 miles;
- a white, red, green or yellow all-round light, 2 miles.

(c) In vessels of less than 12 meters in length:
- a masthead light, 2 miles;
- a sidelight, 1 miles;
- a towing light, 2 miles;
- a white red, green or yellow all-around light, 2 miles.

(d) In inconspicuous, partly submerged vessels or objects being towed;
- a white all-round light; 3 miles.

Rule23. Power driven Vessels Underway

(As amended by the 2001 amendment)

(a) A power driven vessel underway shall exhibit:
- (I) a masthead light forward;
- (II) a second masthead light abaft of and higher than the forward one, except that a vessel of less than 50 meters in length shall not be obliged to exhibit such a light but may do so;
- (III) sidelights:
- (IV) a stern light.

(b) An air-cushion vessel when operating in non-displacement mode shall, in addition to the lights prescribed in paragraph (a) of this Rule, exhibit an all-round flashing yellow light.

(c) A WIG craft when taking off, and in flight near surface shall, in addition to the lights prescribed in paragraph (a) of this rule, exhibit a high intensity all-round flashing red light.

(d)
- (I) A power driven vessel of less than 12 meters in length may in lieu of the lights prescribed in paragraph (a) of this Rule exhibit an all-round white light and sidelights.
- (III) A power driven vessel of less than 7 meters in length whose maximum speed does not exceed 7 knots may in lieu of the lights prescribed in paragraph (a) of this Rule exhibit an all-round white light and shall, if practicable, also exhibit sidelights.
- (IV) The masthead light or all-round white light on a power driven vessel of less than 12 meters in length may be displaced from the fore and aft centreline of the vessel if centreline fitting is not practicable, provided the sidelights are combined in one lantern which shall be carried on the fore and aft centreline of the vessel or located as nearly as practicable in the same fore and aft line as the masthead light or all-round white light.

Rule24. Towing and Pushing

(a) A power driven vessel when towing shall exhibit:
- (I) instead of the light prescribed in Rule 23(a)(I) or (a)(II), two masthead lights in a vertical line. When the length of the tow measuring from the stern of the towing vessel to the after end of the tow exceeds 200 meters, three such lights in a vertical line;
- (II) sidelights;
- (III) a stern light;
- (IV) a towing light in a vertical line above the stern light;
- (V) when the length of the tow exceeds 200 meters, a diamond shape where it can best be seen.

(b) When a pushing vessel and a vessel being pushed ahead are rigidly connected in a composite unit they shall be regarded as a power driven vessel and exhibit the lights prescribed in Rule 23.

(c) A power driven vessel when pushing ahead or towing alongside, except in the case of a composite unit, shall exhibit:

(I) instead of the light prescribed in Rule 23(a)(I) or (a)(II), two masthead lights in a vertical line. When the length of the tow measuring from the stern of the towing vessel to the after end of the tow exceeds 200 meters, three such lights in a vertical line;

(II) sidelights;

(III) a stern light.

(d) A power driven vessel to which paragraph (a) or (c) of this Rule apply shall also comply with rule 23(a)(II).

(e) A vessel or object being towed, other than those mentioned in paragraph (g) of this Rule, shall exhibit:

(I) sidelights;

(II) a stern light;

(III) when the length of the tow exceeds 200 meters, a diamond shape where it can best be seen.

(f) Provided that any number of vessels being towed alongside or pushed in a group shall be lighted as one vessel,

(I) a vessel being pushed ahead, not being part of a composite unit, shall exhibit at the forward end, sidelights;

(II) a vessel being towed alongside shall exhibit a stern light and at the forward end, sidelights.

(g) An inconspicuous, partly submerged vessel or object, or combination of such vessels or objects being towed, shall exhibit:

(I) if it is less than 25 meters in breadth, one all-round white light at or near the front end and one at or near the after end except that dracones need not exhibit a light at or near the forward end;

(II) if it is 25 meters or more in breadth, two or more additional all-round white lights at or near the extremities of its breadth;

(III) if it exceeds 100 meters in length, additional all-round white lights between the lights prescribed in subparagraphs (i) and (ii) so that the distance between the lights shall not exceed 100 meters.;

(IV) a diamond shape at or near the aftermost extremity of the last vessel or object being towed and if the length of the tow exceeds 200 meters an additional diamond shape where it can best be seen and located as far forward as is practicable.

(h) When from any sufficient cause it is impracticable for a vessel or object being towed to exhibit the lights or shapes prescribed in paragraph (e) or (g) of this Rule, all possible measures shall be taken to light the vessel or object being towed or at least indicate the presence of such vessel or object.

(I) Where from any sufficient cause it is impracticable for a vessel not normally engaged in towing operations to display the lights prescribed in paragraph (a) or (c) of this Rule, such vessel shall not be required to exhibit those lights when engaged in towing another vessel in distress or otherwise in need of assistance. All possible measures shall be taken to indicate the nature of the relationship between the towing vessel and the vessel being towed as authorized by Rule 36, in particular by illuminating the towline.

Rule25. Sailing Vessels Underway and Vessels Under Oars

(a) A sailing vessel underway shall exhibit:
   (I) sidelights;
   (II) a stern light.

(b) In a sailing vessel of less than 20 meters in length the lights prescribed in paragraph (a) of this Rule may be combined in one lantern carried at or near the top of the mast where it can best be seen.

(c) A sailing vessel underway may, in addition to the lights prescribed in paragraph (a) of this Rule, exhibit at or near the top of the mast, where they can best be seen, two all-round lights in a vertical line, the upper being red and the lower Green, but these lights shall not be exhibited in conjunction with the combined lantern permitted by paragraph (b) of this Rule.

(d) (I) A sailing vessel of less than 7 meters in length shall, if practicable, exhibit the lights prescribed in paragraph (a) or (b) of this Rule, but if she does not, she shall have ready at hand an electric torch or lighted lantern showing a white light which shall be exhibited in sufficient time to prevent collision.
   (II) A vessel under oars may exhibit the lights prescribed in this rule for sailing vessels, but if she does not, she shall have ready at hand an electric torch or lighted lantern showing a white light which shall be exhibited in sufficient time to prevent collision.

(e) A vessel proceeding under sail when also being propelled by machinery shall exhibit forward where it can best be seen a conical shape, apex downwards.

Rule26. Fishing Vessels

(As amended by the 2001 amendment)

(a) A vessel engaged in fishing, whether underway or at anchor, shall exhibit only the lights and shapes prescribed by this rule.

(b) A vessel when engaged in trawling, by which is meant the dragging through the water of a dredge net or other apparatus used as a fishing appliance, shall exhibit;
   (I) two all-round lights in a vertical line, the upper being green and the lower white, or a shape consisting of two cones with their apexes together in a vertical line one above the other;
   (II) a masthead light abaft of and higher than the all-round green light; a vessel of less than 50 meters in length shall not be obliged to exhibit such a light but may do so;
   (III) when making way through the water, in addition to the lights prescribed in this paragraph, sidelights and a stern light.

(c) A vessel engaged in fishing, other than trawling, shall exhibit:
   (I) two all-round lights in a vertical line, the upper being red and the lower white, or a shape consisting of two cones with their apexes together in a vertical line one above the other;

(II) when there is outlying gear extending more than 150 meters horizontally from the vessel, an all-round white light or a cone apex upwards in the direction of the gear.

(III) when making way through the water, in addition to the lights prescribed in this paragraph, sidelights and a stern light.

(d) The additional signals described in Annex II to these Regulations apply to a vessel engaged in fishing in close proximity to other vessels engaged in fishing.

(e) A vessel when not engaged in fishing shall not exhibit the lights or shapes prescribed in this Rule, but only those prescribed for a vessel of her length.

Rule27. Vessels Not Under Command or Restricted in Their Ability to Manoeuvre

(As amended by the 2001 amendment)

(a) A vessel not under command shall exhibit:

(I) two all-round red lights in a vertical line where they can best be seen;

(II) two balls or similar shapes in a vertical line where they can best be seen;

(III) when making way through the water, in addition to the lights prescribed in this paragraph, sidelights and a stern light.

(b) A vessel restricted in her ability to manoeuvre, except a vessel engaged in mine clearance operations, shall exhibit:

(I) three all-round lights in a vertical line where they can best be seen. The highest and lowest of these lights shall be red and the middle light shall be white;

(II) three shapes in a vertical line where they can best be seen. The highest and lowest of these shapes shall be balls and the middle one a diamond.

(III) when making way through the water, a masthead light, sidelights and a stern light in addition to the lights prescribed in subparagraph (I);

(IV) when at anchor, in addition to the lights or shapes prescribed in subparagraphs (I) and (II), the light, or lights, or shape prescribed in Rule 30.

(c) A power driven vessel engaged in a towing operation such as severely restricts the towing vessel and her tow in their ability to deviate from their course shall, in addition to the lights or shapes prescribed in Rule 24(a), exhibit the lights or shapes prescribed in subparagraph (b)(I) and (II) of this Rule.

(d) A vessel engaged in dredging or underwater operations, when restricted in her ability to manoeuvre, shall exhibit the lights and shapes prescribed in subparagraphs (b)(I),(II) and (III) of this Rule and shall in addition when an obstruction exists, exhibit:

(I) two all-round red lights or two balls in a vertical line to indicate the side on which the obstruction exists;

(II) two all-round green lights or two diamonds in a vertical line to indicate the side on which another vessel may pass;

(III) when at anchor, the lights or shapes prescribed in this paragraph instead of the lights or shapes prescribed in Rule 30.

(e) Whenever the size of a vessel engaged in diving operations makes it impracticable to exhibit all lights and shapes prescribed in paragraph (d) of this Rule, the following shall be exhibited:

(I) Three all-round lights in a vertical line where they can best be seen. The highest and lowest of these lights shall be red and the middle light shall be white;

(II) a rigid replica of the code flag "A" not less than 1 meter in height. Measures shall be taken to ensure its all-round visibility.

(f) A vessel engaged in mine clearance operations shall in addition to the lights prescribed for a power driven vessel in Rule 23 or to the light or shape prescribed for a vessel at anchor in Rule 30 as appropriate, exhibit three all-round green lights or three balls. One of these lights or shapes shall be exhibited near the foremast head and one at each end of the fore yard. These lights or shapes indicate that it is dangerous for another vessel to approach within 1000 meters of the mine clearance vessel.

(g) Vessels of less than 12 meters in length, except those engaged in diving operations, shall not be required to exhibit the lights prescribed in this Rule.

(h) The signals prescribed in this Rule are not signals of vessels in distress and requiring assistance. Such signals are contained in Annex IV to these Regulations.

Rule28. Vessels Constrained by their Draft

A vessel constrained by her draft may, in addition to the lights prescribed for power driven vessels in Rule 23, exhibit where they can best be seen three all-round red lights in a vertical line, or a cylinder.

Rule29. Pilot Vessels

(a) A vessel engaged on pilotage duty shall exhibit:

(I) at or near the masthead, two all-round lights in a vertical line, the upper being white and the lower red;

(II) when underway, in addition, sidelights and a stern light;

(III) when at anchor, in addition to the lights prescribed in subparagraph (I), the light, lights, or shape prescribed in Rule 30 for vessels at anchor.

(b) A pilot vessel when not engaged on pilotage duty shall exhibit the lights or shapes prescribed for a similar vessel of her length.

Rule30. Anchored Vessels and Vessels Aground

(a) A vessel at anchor shall exhibit where it can best be seen:

(I) in the fore part, an all-round white light or one ball;

(II) at or near the stern and at a lower level than the light prescribed in subparagraph (I), an all-round white light.

(b) A vessel of less than 50 meters in length may exhibit an all-round white light where it can best be seen instead of the lights prescribed in paragraph (a) of this Rule.

(c) A vessel at anchor may, and a vessel of 100 meters and more in length shall, also use the available working or equivalent lights to illuminate her decks.

(d) A vessel aground shall exhibit the lights prescribed in paragraph (a) or (b) of this Rule and in addition, where they can best be seen;

  (I) two all-round red lights in a vertical line;

  (II) three balls in a vertical line.

(e) A vessel of less than 7 meters in length, when at anchor not in or near a narrow channel, fairway or where other vessels normally navigate, shall not be required to exhibit the lights or shape prescribed in paragraphs (a) and (b) of this Rule.

(f) A vessel of less than 12 meters in length, when aground, shall not be required to exhibit the lights or shapes prescribed in subparagraphs (d)(I) and (II) of this Rule.

Rule31. Seaplanes

(As amended by the 2001 amendment)

Where it is impracticable for a seaplane to exhibit lights or shapes of the characteristics or in the positions prescribed in the Rules of this Part she shall exhibit lights and shapes as closely similar in characteristics and position as is possible.

Part D - Sound and Light Signals

Rule32. Definitions

(a) The word **"whistle"** means any sound signalling appliance capable of producing the prescribed blasts and which complies with the specifications in Annex III to these Regulations.

(b) The term **"short blast"** means a blast of about one second's duration.

(c) The term **"prolonged blast"** means a blast from four to six seconds' duration.

Rule33. Equipment for Sound Signals

(As amended by the 2001 amendment)

(a) A vessel of 12 meters or more in length shall be provided with a whistle and a bell and a vessel of 100 meters or more in length shall, in addition be provided with a gong, the tone and sound of which cannot be confused with that of the bell. The whistle, bell and gong shall comply with the specifications in Annex III to these Regulations. The bell or gong or both may be replaced by other equipment having the same respective sound characteristics, provided that manual sounding of the prescribed signals shall always be possible.

(b) A vessel of less than 12 meters in length shall not be obliged to carry the sound signalling appliances prescribed in paragraph (a) of this Rule but if she does not, she shall be provided with some other means of making an efficient signal.

Rule34. Manoeuvring and Warning Signals

(a) When vessels are in sight of one another, a power driven vessel under way, when manoeuvring as authorized or required by these Rules, shall indicate that manoeuvre by the following signals on her whistle:
- one short blast to mean "I am altering my course to starboard";
- two short blasts to mean "I am altering my course to port";
- three short blasts to mean "I am operating astern propulsion".

(b) Any vessel may supplement the whistle signals prescribed in paragraph (a) of this Rule by light signals, repeated as appropriate, whilst the manoeuvre is being carried out:

(I) these signals shall have the following significance:
- one flash to mean "I am altering my course to starboard";
- two flashes to mean "I am altering my course to port";
- three flashes to mean "I am operating astern propulsion".

(II) the duration of each flash shall be about one second, the interval between flashes shall be about one second, and the interval between successive signals shall not be less than ten seconds.

(III) the light used for this signal shall, if fitted, be an all-round white light, visible at a minimum range of 5 miles, and shall comply with the provisions of Annex I to these Regulations.

(c) When in sight of one another in a narrow channel or fairway:

(I) a vessel intending to overtake another shall in compliance with Rule 9 (e)(I) indicate her intention by the following signals on her whistle.
- two prolonged blasts followed by one short blast to mean "I intend to overtake you on your starboard side";
- two prolonged blasts followed by two short blasts to mean "I intend to overtake you on your port side".

(II) the vessel about to be overtaken when acting in accordance with 9(e)(I) shall indicate her agreement by the following signal on her whistle:
- one prolonged, one short, one prolonged and one short blast, in that order.

(d) When vessels in sight of one another are approaching each other and from any cause either vessel fails to understand the intentions or actions of the other, or is in doubt whether sufficient action is being taken by the other to avoid collision, the vessel in doubt shall immediately indicate such doubt by giving at least five short and rapid blasts on the whistle. Such signal may be supplemented by at least five short and rapid flashes.

(e) A vessel nearing a bend or an area of a channel or fairway where other vessels may be obscured by an intervening obstruction shall sound one prolonged blast. Such signal shall be answered with a prolonged blast by any approaching vessel that may be within hearing around the bend or behind the intervening obstruction.

(f) If whistles are fitted on a vessel at a distance apart of more than 100 meters, one whistle only shall be used for giving manoeuvring and warning signals.

Rule35. Sound Signals in Restricted Visibility

(As amended by the 2001 amendment)

In or near an area of restricted visibility, whether by day or night the signals prescribed in this Rule shall be used as follows:

(a) A power driven vessel making way through the water shall sound at intervals of not more than 2 minutes one prolonged blast.

(b) A power driven vessel underway but stopped and making no way through the water shall sound at intervals of no more than 2 minutes two prolonged blasts in succession with an interval of about 2 seconds between them.

(c) A vessel not under command, a vessel restricted in her ability to maneuver, a vessel constrained by her draft, a sailing vessel, a vessel engaged in fishing and a vessel engaged in towing or pushing another vessel shall, instead of the signals prescribed in paragraph (a) or (b) of this Rule, sound at intervals of not more than 2 minutes three blasts in succession, namely one prolonged followed by two short blasts.

(d) A vessel engaged in fishing, when at anchor, and a vessel restricted in her ability to maneuver when carrying out her work at anchor, shall instead of the signals prescribed in paragraph (g) of this Rule sound the signal prescribed in paragraph (c) of this Rule.

(e) A vessel towed or if more than one vessel is being towed the last vessel of the tow, if manned, shall at intervals of not more than 2 minutes sound four blasts in succession, namely one prolonged followed by three short blasts. When practicable, this signal shall be made immediately after the signal made by the towing vessel.

(f) When a pushing vessel and a vessel being pushed ahead are rigidly connected in a composite unit they shall be regarded as a power driven vessel and shall give the signals prescribed in paragraphs (a) or (b) of this Rule.

(g) A vessel at anchor shall at intervals of not more than 1 minute ring the bell rapidly for five seconds. In a vessel 100 meters or more in length the bell shall be sounded in the forepart of the vessel and immediately after the ringing of the bell the gong shall be sounded rapidly for about 5 seconds in the after part of the vessel. A vessel at anchor may in addition sound three blasts in succession, namely one short, one long and one short blast, to give warning of her position and of the possibility of collision to an approaching vessel.

(h) A vessel aground shall give the bell signal and if required the gong signal prescribed in paragraph (g) of this Rule and shall, in addition, give three separate and distinct strokes on the bell immediately before and after the rapid ringing of the bell. A vessel aground may in addition sound an appropriate whistle signal.

(i) A vessel of less than 12 meters in length shall not be obliged to give the above mentioned signals but, if she does not, shall make some other efficient sound signal at intervals of not more than 2 minutes.

(j) A pilotage vessel when engaged on pilotage duty may in addition to the signals prescribed in paragraph (a), (b) or (g) of this Rule sound an identity signal consisting of four short blasts.

Rule36. Signals to Attract Attention

If necessary to attract the attention of another vessel, any vessel may make light or sound signals that cannot be mistaken for any signal authorized elsewhere in these Rules, or may direct the beam of her searchlight in the direction of the danger, in such a way as not to embarrass any vessel Any light to attract the attention of another vessel shall be such that it cannot be mistaken for any aid to navigation. For the purpose of this Rule the use of high intensity intermittent or revolving lights, such as strobe lights, shall be avoided.

Rule37. Distress Signals

When a vessel is in distress and requires assistance she shall use or exhibit the signals described in Annex IV to these Regulations.

Part E - Exemptions

Rule38. Exemptions

(As amended by the 2001 amendment)

Any vessel (or class of vessel) provided that she complies with the requirements of the **International Regulations for the Preventing of Collisions at Sea, 1960**, the keel of which is laid or is at a corresponding stage of construction before the entry into force of these Regulations may be exempted from compliance therewith as follows:

(a) The repositioning of lights as a result of conversion from Imperial to metric units and rounding off measurement figures, permanent exemption

(b) (I) The repositioning of masthead lights on vessels of less than 150 meters in length, resulting from the prescriptions of Section 3 (a) of Annex I to these regulations, permanent exemption

(II) The repositioning of masthead lights on vessels of 150 meters or more in length, resulting from the prescriptions of Section 3 (a) of Annex I to these regulations, until 9 years after the date of entry into force of these Regulations.

(c) The repositioning of masthead lights resulting from the prescriptions of Section 2(b) of Annex I to these Regulations, until 9 years after the date of entry into force of these Regulations.

(d) The repositioning of sidelights resulting from the prescriptions of Section 2(g) and 3(b) of Annex I to these Regulations, until 9 years after the date of entry into force of these Regulations.

(e) The requirements for sound signal appliances prescribed in Annex II to these Regulations, until 9 years after the date of entry into force of these Regulations

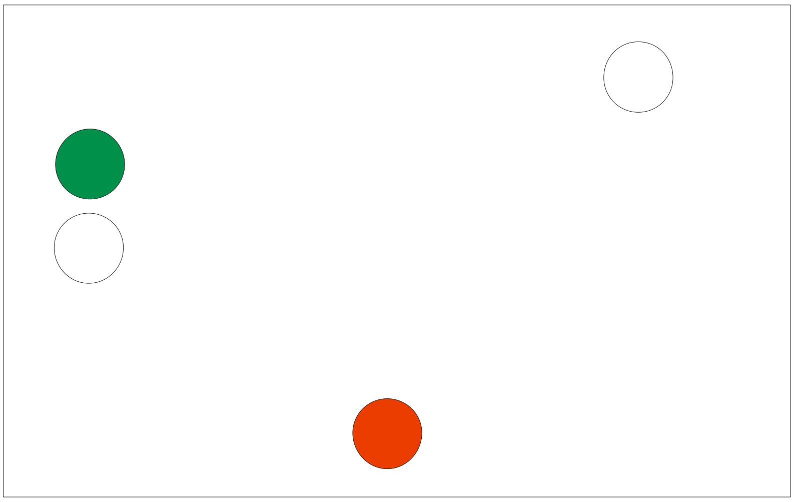
(f) The repositioning of all-round lights resulting from the prescription of Section 9(b) of Annex I to these Regulations, permanent exemption

(g) .The installation of lights with ranges prescribed in Rule 22, until 4 years after the date of entry into force of these regulations

(h) The installation of lights with colour specifications as prescribed in Section 7 of Annex I to these Regulations, until 4 years after the entry into force of these Regulations

6250 Examples for the application of the Rules to prevent collision at sea

Example 1 *The 15m LOA sailing vessel (A) is sailing with a 16 Kn NNW Wind on Port tack a true course of RwK=040° at a speed of app. 5 Kn. In a relative (Side) bearing of SB=60° (A) observes an object (B) exhibiting the following lights.*



Although the change of the side bearing is marginal, the distance between the vessels is continuously decreasing.

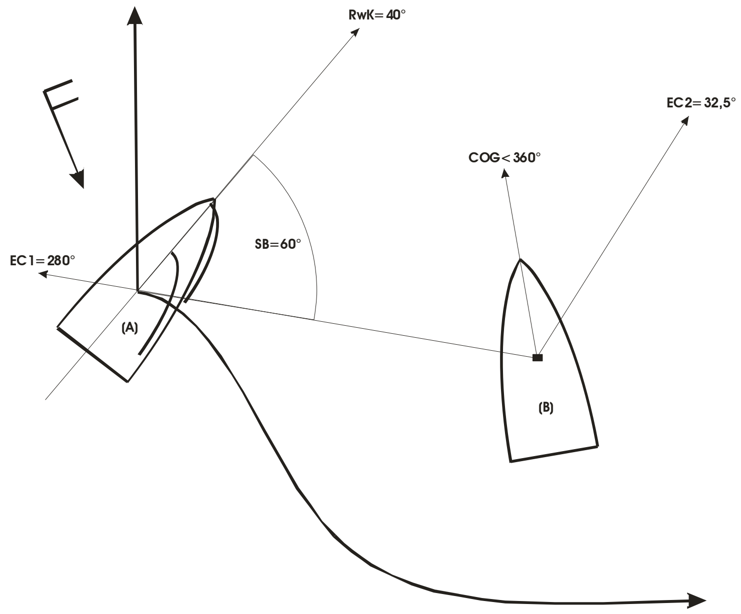
1.1 What type of information can be extracted from this observation?

1.2 Within which extreme courses is (B) moving? What is the most probable course of (B)?

1.3 Is there a risk of collision? If yes which vessel shall alter course to avoid collision?

1.4 Describe the actions to be taken by the vessel obliged to alter course to avoid collision.

Answer *1.1 (B) is a fishing vessel with a LOA>50m engaged in trawling, making way and exhibiting its port side to (A).*



1.2 The port side light of (B) is visible for (A) if (B) is heading directly down to (A) i.e. with an extreme course EC1=360°-(180°-RwK-SB)=360°-(180°-40°-60°)=280°. Due to the fact the arc of visibility of a side light has to be 112,5°, the red side light of (B) is still visible for (A) even if (B) is heading EC2=EC1+112,5°-360°= 32,5°. From the observed configuration of the lights especially the fact the Masthead light appears very close to the two all-round lights and the fact the distance between the vessels is decreasing, it has to be assumed that (Bs) most probable heading is: 280°<COG<360° .

1.3 Due to the fact the side bearing does not change significantly, there is a risk of collision and (A) has to alter course to avoid impedance of the passage of (B).

1.4 (A) can alter course to starboard and pass under the stern of (B). However (A) shall maintain a safe distance from (B), as the trawler may have deployed nets with a length of some 1.000m.

Example 2 ***S****ailing yacht (A) is sailing with a SE breeze a RwK=315°. About 2 Sm Northward of (A) there is another yacht (B) under sails steering app. 280°. Westward of (A) a yacht (C) under sails is observed steering app. 350°. The side bearings from (B) and (C) taken from (A) do not change, and the distances between the three vessels are continuously decreasing.*
2.1 Is there a risk of collision from (A) stand point of view?

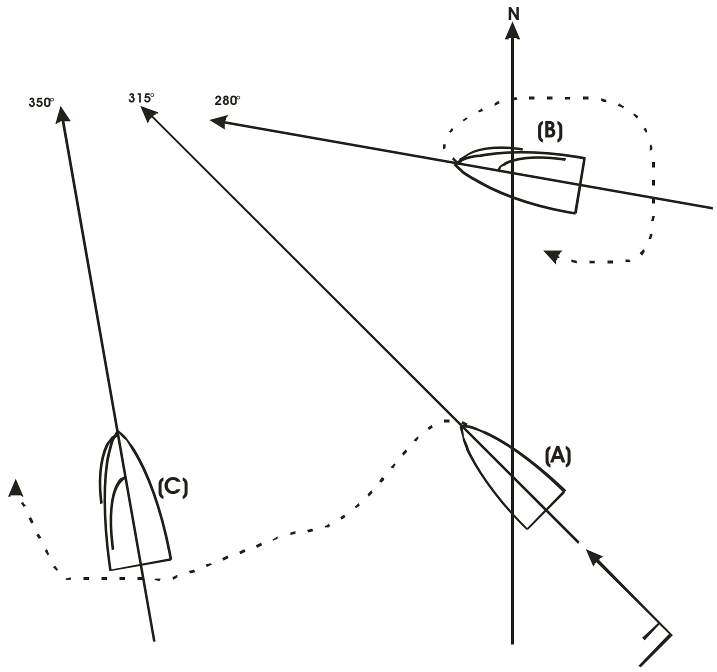
2.2 Which actions have to be taken to avoid collision?

2.3 Which actions would have to be taken if this situation would arise at night?

Answer

2.1 From (As) stand point of view there is a risk of collision as the side bearings to the other vessels are not changing and the distances are continuously decreasing.

2.2 The actions to be taken to avoid collision are depending upon the answer to the question on which tack (A) is sailing.



With (A) on starboard tack:

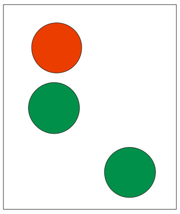
- *As (C) is sailing on starboard tack and is with respect to (A) the leeward yacht she shall maintain her course and both (A) and (B) shall keep out of her way.*
- *As (A) is the windward vessel against (C) she shall keep out of the way of (C), and shall therefore alter course to port to pass under her stern.*
- *In order to avoid impedance of the passage of (C), (B) will have to change her course to starboard*

With (A) on port tack:

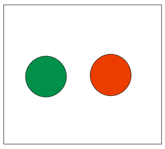
- *As (C) is sailing on starboard tack she shall maintain her course and both (A) and (B) shall keep out of her way.*
- *In order to avoid impedance of the passage of (C), (A) will have to change her course to port to pass under the stern of (C).*
- *In order to avoid impedance of the passage of (C), (B) will have to change her course to starboard.*
- *Following the course alteration to port in order to avoid collision with (C), although (A) is sailing on the same tack as (B), she shall keep out of the way of the leeward yacht (B), and shall therefore change again her course to starboard to pass under the stern of (B).*

2.3 (B) and (C) shall assume the worst case situation which means that (A) is on starboard tack.

Example 3 *A 12m sailing yacht (A) is sailing with a north wind of 3 Beaufort a RwK=70° and observe on her port bow in a side bearing of 60° the following lights of (B):*



Dead ahead of (A) another vessel (C) exhibits the following lights:



The side bearing of the vessels (B) and (C) do not change significantly, whilst the distances to (A) are rapidly decreasing.

3.1 What type of information can be extracted from the light configuration exhibited by (B)?

3.2 Within which extreme courses is (B) moving?

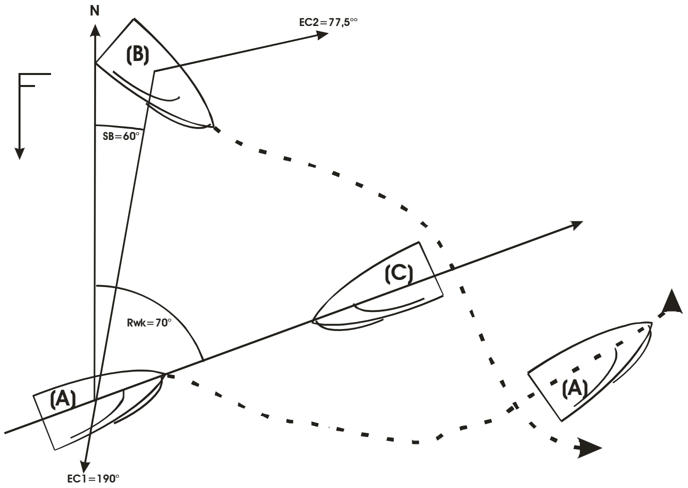
3.3 Is there a risk of collision and is (A) obliged to keep out of the way of the other vessels?

3.4 Which actions shall be taken by (A)?

Answer *3.1 (B) is a sailing vessel under way exhibiting its starboard side to (A).*

3.2 The starboard side light of (B) is visible for (A) if (B) is heading directly down to (A) i.e. with an extreme course EC1=RwK-SB+180°=70°-60°+180°=190°. Due to the fact the arc of visibility of a side light has to be 112,5°, the green side light of (B) is still visible for (A) even if (B) is heading EC2=EC1-112,5°=190°-112,5°=77,5°

3.3 (B) can not be on starboard tack, as in this particular case (B) would have to steer a course >180° and this would lead to a changing side bearing at (A). Due to the fact the side bearing is not changing (B) is on Port tack and has therefore to keep out of the way of (A) being the leeward vessel and out of the way of (C) which is sailing on starboard tack.



(A) will have to keep out of the way of (C) as the is no doubt that (C) is sailing on Starboard tack.

3.4 (A) shall change course to starboard in order to avoid impedance of the passage of (C), but shall subsequently maintain it course against (B).

PART 6

(Maritime safety and communications)

Chapter 3

(Maritime communications)

6310 Generation of radio waves

Consider electric current as a flow of electrons along a conductor between points of differing potential. A **direct current** flows continuously in the same direction. This would occur if the polarity of the electromotive force causing the electron flow was constant, such as is the case with a battery. If, however, the current is induced by the relative motion between a conductor and a magnetic field, as is the case in a rotating machine, called a **generator**, then the resulting current changes direction in the conductor as the polarity of the electromotive force changes with the rotation of the generator's rotor. This is known as **alternating current**.

The energy of the current flowing through the conductor is either dissipated as heat (an energy loss proportional to both the current flowing through the conductor and the conductor's resistance) or stored in an electromagnetic field oriented symmetrically about the conductor. The orientation of this field is a function of the polarity of the source producing the current. When the current is removed from the wire, this electromagnetic field will, after a finite time, collapse back into the wire.

What would occur should the polarity of the current source supplying the wire be reversed at a rate which exceeds the finite amount of time required for the electromagnetic field to collapse back upon the wire? In this case, another magnetic field, proportional in strength but exactly opposite in magnetic orientation to the initial field, will be formed upon the wire. The initial magnetic field, its current source gone, cannot collapse back upon the wire because of the existence of this second electromagnetic field. Instead, it propagates out into space. This is the basic principle of a radio antenna, which transmits a wave at a frequency proportional to the rate of pole reversal and at a speed equal to the speed of light.

6320 The electromagnetic spectrum

The entire range of electromagnetic radiation frequencies is called the electromagnetic spectrum. The frequency range suitable for radio transmission, the radio spectrum, extends from 10 kilohertz to 300,000 megahertz. It is divided into a number of bands, as shown in Figure 6320a below.

Below the radio spectrum, but overlapping it, is the audio frequency band, extending from 20 to 20,000 hertz. Above the radio spectrum are heat and infrared, the visible spectrum (light in its various colours), ultraviolet, X-rays, gamma rays, and cosmic rays. Waves shorter than 30 centimetres are usually called microwaves.

Within the frequencies from 1-40 GHz (1,000-40,000 MHz), additional bands are defined as follows:

- L-band: 1-2 GHz (1,000-2,000 MHz)
- S-band: 2-4 GHz (2,000-4,000 MHz
- C-band: 4-8 GHz (4,000-8,000 MHz)
- X-band: 8-12.5 GHz (8,000-12,500 MHz)
- Lower K-band: 12.5-18 GHz (12,500-18,000 MHz)
- Upper K-band: 26.5-40 GHz (26,500-40,000 MHz)

Marine radar systems commonly operate in the S and X bands, while satellite navigation system signals are found in the L-band. The break of the K-band into lower and upper ranges is necessary because the resonant frequency of water vapour occurs in the middle region of this band, and severe absorption of radio waves occurs in this part of the spectrum.

Band	Abbreviation	Range of frequency	Range of wavelength
Audio frequency	AF	20 to 20,000 Hz	15,000,000 to 15,000 m
Radio frequency	RF	10 kHz to 300,000 MHz	30,000 m to 0.1 cm
Very low frequency	VLF	10 to 30 kHz	30,000 to 10,000 m
Low frequency	LF	30 to 300 kHz	10,000 to 1,000 m
Medium frequency	MF	300 to 3,000 kHz	1,000 to 100 m
High frequency	HF	3 to 30 MHz	100 to 10 m
Very high frequency	VHF	30 to 300 MHz	10 to 1 m
Ultra high frequency	UHF	300 to 3,000 MHz	100 to 10 cm
Super high frequency	SHF	3,000 to 30,000 MHz	10 to 1 cm
Extremely high frequency	EHF	30,000 to 300,000 MHz	1 to 0.1 cm
Heat and infrared*		10^6 to 3.9×10^8 MHz	0.03 to 7.6×10^{-5} cm
Visible spectrum*		3.9×10^8 to 7.9×10^8 MHz	7.6×10^{-5} to 3.8×10^{-5} cm
Ultraviolet*		7.9×10^8 to 2.3×10^{10} MHz	3.8×10^{-5} to 1.3×10^{-6} cm
X-rays*		2.0×10^9 to 3.0×10^{13} MHz	1.5×10^{-5} to 1.0×10^{-9} cm
Gamma rays*		2.3×10^{12} to 3.0×10^{14} MHz	1.3×10^{-8} to 1.0×10^{-10} cm
Cosmic rays*		$>4.8\times10^{15}$ MHz	$<6.2\times10^{-12}$ cm

* Values approximate.

Figure 6320a Electromagnetic spectrum

Within the VHF band and in the area of 150 MHz, 59 channels are according to GMDSS requirements reserved for maritime communications. Those are the channels 01 to 28, the channels 60 to 88 plus two additional channels reserved for the Automatic Identification System (AIS). For further details refer to Figure 6320b below.

Channels		Station Frequencies		Ship	Harbour traffic control		Public
		See	Shore	Ship	Simplex	Duplex	communications
	60	156,025	160,625			x	x
1		156,050	160,650			x	x
	61	156,075	160,675			x	x
2		156,100	160,700			x	x
	62	156,125	160,725			x	x
3		156,150	160,750			x	x
	63	156,175	160,775			x	x
4		156,200	160,800			x	x
	64	156,225	160,825			x	x
5		156,250	160,850			x	x
	65	156,275	160,875			x	x
6		156,300		x			
	66	156,325	160,925			x	x
7		156,350	160,950			x	x
	67	156,375	156,375	x	x		
8		156,400		x			
	68	156,425	156,425		x		
9		156,450	156,450	x	x		
	69	156,475	156,475	x	x		
10		156,500	156,500	x	x		
	70	156,525	156,525	Digital selective calling (distress, urgency and safety communication)			
11		156,550	156,550		x		
	71	156,575	156,575		x		
12		156,600	156,600		x		
	72	156,625		x			
13		156,650	156,650	x	x		
	73	156,675	156,675	x	x		
14		156,700	156,700		x		
	74	156,725	156,725		x		
15		156,750	156,750	x	x		
	75	156,775			x		
16		156,800	156,800	Distress, urgency, safety and calling channel.			
	76	156,825			x		
17		156,850	156,850	x	x		
	77	156,875		x			
18		156,900	161,500		x	x	x
	78	156,925	161,525			x	x
19		156,950	161,550			x	x
	79	156,975	161,575			x	x
20		157,000	161,600			x	x
	80	157,025	161,625			x	x
21		157,050	161,650			x	x
	81	157,075	161,675			x	x
22		157,100	161,700			x	x
	82	157,125	161,725		x	x	x
23		157,150	161,750			x	x
	83	157,175	161,775		x	x	x
24		157,200	161,800			x	x
	84	157,225	161,825		x	x	x
25		157,250	161,850			x	x
	85	157,275	161,875		x	x	x
26		157,300	161,900			x	x
	86	157,325	161,925		x	x	x
27		157,350	161,950			x	x
	87	157,375			x		
28		157,400	162,000			x	x
	88	157,425			x		
AIS 1		161,975	161,975				
AIS 2		162,025	162,025				

Figure 6320b Maritime communication channels

6330 Antenna Characteristics

Antenna design and orientation have a marked effect upon radio wave propagation. For a single-wire antenna, strongest signals are transmitted along the perpendicular to the wire and virtually no signal in the direction of the wire. For a vertical antenna, the signal strength is the same in all horizontal directions. Unless the polarisation undergoes a change during transit, the strongest signal received from a vertical transmitting antenna occurs when the receiving antenna is also vertical.
For a vertical antenna, efficiency increases with greater length of the antenna. The power received is inversely proportional to the square of the distance from the transmitter, assuming there is no attenuation of the wave.

For a typical VHF equipment with a vertical antenna transmitting e.g. on Chanel 16 i.e. on 156,8 MHz, a minimum antenna length of :

$$\frac{\lambda}{4} = 300.000\frac{Km}{\sec} * \frac{1}{156{,}8MHz} = 47{,}83cm$$

6340 VHF Horizon

The VHF horizon is greater than the horizon of the radar, whilst the radar horizon is greater than the optical one. The distances in said cases in nautical miles are approximately the following (All heights in meters):

- Optical horizon: $D_{Opt} = 2{,}075 * \left(\sqrt{h_{Observer}} + \sqrt{h_{Light}}\right)$
- Radar horizon: $D_{Radar} = 2{,}23 * \left(\sqrt{h_{Radar}} + \sqrt{h_{Obstruction}}\right)$
- VHF horizon: $D_{VHF} = 2{,}5 * \left(\sqrt{h_{Transmitter}} + \sqrt{h_{Receiver}}\right)$

6350 Message Type Priorities

The following message type priorities are recognized by GMDSS including DSC.

- Routine messages
- Safety messages
- Urgency messages
- Distress messages

6351 Routine communication format

Routine calls are normally addressed to a single coast or ship station. They should be made on a channel reserved for non-distress traffic. Once made, a call should not be repeated, since the receiving station either received the call and stored it, or did not receive it because it was not in service. At least 5 minutes should elapse between calls by vessels on the first attempt, then at 15 minute minimum intervals. To initiate a routine ship to shore or ship to ship call to a specific station, the following procedures are applied.

DSC call

<u>Call to a shore station with unknown working Chanel.</u>

- VHF on Chanel 70
- Format: Selective call.
- MMSI of the shore station.
- Category: Routine.
- Telecom: Phone.
- Proposed Working Chanel: **<u>Non.</u>**
- Submit.

Acknowledgment

- MMSI of the station.
- Format: Acknowledge able.
- Telecom: Phone.
- Working Chanel: *(e.g. Ch 28).*

Reply to shore station

(See Non – GMDSS)

Confirmation by the shore station

(See Non – GMDSS)

<u>Call to a ship station</u>

- VHF on Chanel 70.
- Format: Selective call.
- MMSI of the ship station.
- Category: Routine.
- Telecom: Simplex.
- Proposed Working Chanel: *(e.g. Ch 28).*
- Submit.

Acknowledgment by the ship station

- MMSI of the ship station.
- Format: acknowledge able.
- Telecom: simplex.
- Working Chanel: *(e.g. Ch 28).*

Reply to ship station

Non – GMDSS

<u>Call to a shore station with known working Chanel or on Chanel 16:</u>

- VHF on Stations working Chanel.
- Call station with its official designation *(e.g. Olympia radio 3x).*
- Vessels name and call sign *(This is…).*
- Reason for calling *(I have a call for you)*
- Over

Acknowledgment

- MMSI of the station.
- Call stations designation *(This is…).*
- Type of required services *(e.g. What can I do for you?).*

Reply to shore station

- Vessels name and MMSI *(this is..).*
- Requested services *(e.g. I have a telephone call to*....).
- Accounting authority identification number *(AAIC is …DP07).*
- Over.

Confirmation by the shore station

- Vessels name and call sign.
- Call stations designation *(This is…).*
- Instructions from the station *(please stand by…).*

<u>Call to a ship station :</u>

- VHF on Chanel 16.
- Call ship station with its name *(and its call sign if known 3x).*
- Calling vessels name and call sign *(This is…3x).*
- Reason for calling *(I have a question).*
- Notification of the proposed working Chanel.
- Over.

Acknowledgment by the ship station

- Name of the calling vessel.
- Ship stations designation *(This is…).*
- Acknowledgment of the working Chanel or proposal for an other Chanel.

Reply to ship station

Communication on the agreed working Chanel.

6352 Safety communication format

Safety messages are transmitted in order to distribute navigational or weather warnings for hazards affecting every body at sea.

DSC call

- VHF on Chanel 70.
- Format: all ships.
- Category: Safety.
- Chanel: Ch 16.
- Telecom: Simplex.
- Submit.

Acknowledgment

No acknowledgement required.

Transmission of the information

- VHF on Chanel 16.
- SECURITE (3x).
- ALL STATIONS (3x).
- MMSI of the station, its name and call sign *(This is…).*
- Safety message.
- Over.

Cancellation of the safety warning

(See Non – GMDSS)

Non – GMDSS

- VHF on Chanel 16.
- SECURITE (3x).
- ALL STATIONS (3x).
- Name of the station *(3x)* and call sign *(This is…).*
- Safety message.
- Over

Acknowledgment

No acknowledgement required.

Cancellation of the safety warning

Safety messages should additionally be offered to the nearest coast station too. The coast station will than decide whether or not the message will be distributed by NAVTEX and will take care for the cancellation of the warning.

6353 Urgency communication format

An urgency message of a station distributes information affecting the safety of a vessel or of an individual person.

DSC call

- VHF on Chanel 70.
- Format: all ships.
- Category: Urgency.
- Chanel: Ch 16.
- Telecom: Simplex.
- Submit.

Acknowledgment

No acknowledgement required.

Transmission of the information

- VHF on Chanel 16.
- PAN PAN (3x).
- ALL STATIONS (3x).
- MMSI of the station, its name and call sign *(This is…).*
- Urgency message.
- Over

Cancellation of the safety warning

(See Non – GMDSS)

Non – GMDSS

- VHF on Chanel 16.
- PAN PAN (3x).
- ALL STATIONS (3x).
- Name of the station and call sign *(This is…).*
- Urgency message.
- Over.

Acknowledgment

No acknowledgement required.

Cancellation of the safety warning

Urgency messages transmitted to all stations shall be cancelled if no further actions are required, as follows:

- VHF on Chanel 16.
- ALL STATIONS (3x).
- Name of the station *(3x)* and call sign *(This is…).*
- *(date time)* UTC.
- Name of the station which issued the urgency message.
- URGENCY TRAFIC FINI.
- Over.

6354 Distress communication format

A distress case exists if a vessel or an individual person faces a serious, immediate and not avertable danger.

DSC call

Once activated, a distress signal is repeated automatically every few minutes until an acknowledgment is received or the function is switched off. The DSC distress signal is activated by a specific "Distress button", is transmitted on Ch 70 and must contain the following information:

- VHF an Chanel 70.
- Format: Distress.
- MMSI of the vessel in distress.
- Nature of distress *(As offered from the VHF)*.
- Latest known position of the vessel in distress.
- Time at which the position has been determined.
- Category: Distress.
- Telecom: Simplex.
- Submit.

Acknowledgment

The receiving stations shall monitor Ch 16 for 5´ after receipt of the distress signal. Within this period the MRCC will normally acknowledge the distress signal by DSC. Acknowledgement by the MRCC is always addressed to *All Stations* in order to make sure that all receiving stations are aware that the MRCC has already received the distress signal. Acknowledgment of a distress signal by DSC stops the automatic repetition of the transmission of the distressed signal. Receiving stations are not authorised to acknowledge distress signals by DSC, unless explicitly authorised by the MRCC. After a period of 5´ and if the receiving station can offer appropriate assistance should acknowledge the receipt of the distress signal on Chanel 16 as follows:

- VHF on Chanel 16.
- MAYDAY
- MMSI of the vessel in distress *(3x).*
- Name of the receiving station *(3x)* and call sign. *(This is…)*
- *Received MAYDAY.*

Non – GMDSS

- VHF on Chanel 16.
- MAYDAY (3x)
- Name of the vessel in distress *(3x)* and call sign. *(This is…)*
- MAYDAY, Name of the vessel in distress and call sign.
- Vessels position.
- Nature of distress.
- Type of assistance required.
- Any further useful information.
- Over.

Acknowledgment

Confirmation is expected from RCC first. However if a receiving station is in the position to offer appropriate assistance to the transmitting station, the receipt of the distress message should be acknowledged as follows:

- VHF on Chanel 16.
- MAYDAY.
- Name of the vessel in distress *(3x)* and call sign.
- Name of the receiving station *(3x)* and call sign. *(This is…).*
- *Received MAYDAY.*

Transmission of detail information

Following the acknowledgment of receipt of the distress signal either by DSC through a MRCC or by Ch 16 by another station, the calling station should immediately start transmission of detail information with respect to as follows:

- VHF on Chanel 16.
- MAYDAY.
- MMSI, name and call sign of the vessel in distress *(This is…).*
- Vessels position.
- Detail information of the nature of distress and the required assistance.
- Over.

Offer of assistance

(See Non – GMDSS)

Offer of assistance

- VHF on Chanel 16.
- MAYDAY, Name and call sign of the vessel in distress.
- Name and call sign of the receiving station *(This is…).*
- When and what kind of assistance is offered.
- Over.

Request for silence

(See Non – GMDSS)

Request for silence

Request for silence in case of distress can be addressed to all stations or a specific station disturbing the communication as follows:

- All stations, or name of a station.
- SILENCE MAYDAY.

Cancellation of a distress warning

(See Non – GMDSS)

Cancellation of a distress warning

After completion of all activities initiated because of a distress, the MRCC or the on-scene co-ordinator shall cancel the distress communication as follows:

- VHF on Chanel 16.
- MAYDAY
- All stations *(3x).*
- Name and call sign of the station authorised to cancel the distress communication *(This is…).*
- at *(time)* UTC.
- Name and call sign of the vessel in distress.
- SILENCE FINI.

Transmission of a distress warning by a station which is not in a distress situation.

In general no station is authorized to relay a distress signal received by DSC to all stations or a MRCC. However, if a station has knowledge of a distress situation either by own observation or transmission on Chanel 16, it should relay a distress signal either to all stations or the MRCC as follows:

- VHF on Chanel 70.
- Format: Distress relay.
- MMSI of the MRCC or all ships.
- Category: Distress
- Telecom: Simplex.
- Position of the vessel in distress if known.
- Submit.

Transmission of a distress warning by a station which is not in a distress situation.

Content of the distress message

- VHF on Chanel 16.
- MAYDAY.
- MMSI, Name and call sign of the relaying vessel. *(This is…).*
- Vessels position.
- Information concerning the time, position *(if known)*, and the nature of distress as received on Ch 16 or according to own observation.
- Name and call sign of the relaying vessel. *(This is…).*
- Over.

Content of the distress message

- VHF on Chanel 16.
- MAYDAY RELAY *(3x).*
- Name *(3x)* and call sign of the relaying vessel. *(This is…).*
- Vessels position.
- Information concerning the time, position *(if known)*, and the nature of distress as received on Ch 16 or according to own observation.
- Name and call sign of the relaying vessel. *(This is…).*
- Over

Cancellation of an erroneously issued distress warning.

The issue of a distress signal causes all affected station to stand by at Chanel 16. It is therefore not necessary to cancel an erroneously issued distress warning by DAC.

- VHF on Chanel 16.
- ALL STATIONS *(3x).*
- MMSI, Name and call sign of the vessel which issued the distress warning *(This is…).*
- Vessels position.
- Please cancel my distress alert from *(Datetime) UTC.*
- Masters name.
- *(Datetime) UTC.*

Cancellation of an erroneously issued distress warning.

(Not applicable.)

APPENDIX A

(Refraction Table)

Refraction deviation angles **(R)** for an observer at sea level, for apparent (rectified) altitude angles of astronomical lines of sight **(ha)** through a standard atmosphere.

Observed Apparent altitude (ha)		**Refraction Deviation (R)**	**Observed apparent altitude (ha)**	**Refraction deviation (R)**
(deg)	**(min)**	**(min)**	**(deg)**	**(min)**
0	**00**	**34,5**	**10**	**5,3**
0	**15**	**31,4**	**11**	**4,9**
0	**30**	**28,7**	**12**	**4,5**
0	**45**	**26,4**	**13**	**4,1**
1	**00**	**24,3**	**14**	**3,8**
1	**15**	**22,5**	**15**	**3,6**
1	**30**	**20,9**	**16**	**3,3**
1	**45**	**19,5**	**17**	**3,1**
2	**00**	**18,3**	**18**	**2,9**
2	**15**	**17,2**	**19**	**2,8**
2	**30**	**16,1**	**20**	**2,6**
2	**45**	**15,2**	**25**	**2,1**
3	**00**	**14,4**	**30**	**1,7**
3	**30**	**12,9**	**35**	**1,4**
4	**00**	**11,8**	**50**	**0,8**
4	**30**	**10,7**	**55**	**0,7**
5	**00**	**9,9**	**60**	**0,6**
6	**00**	**8,5**	**65**	**0,5**
7	**00**	**7,4**	**70**	**0,4**
8	**00**	**6,6**	**80**	**0,2**
9	**00**	**5,9**	**90**	**0,0**

APPENDIX B

(Navigational stars epoch 2010)

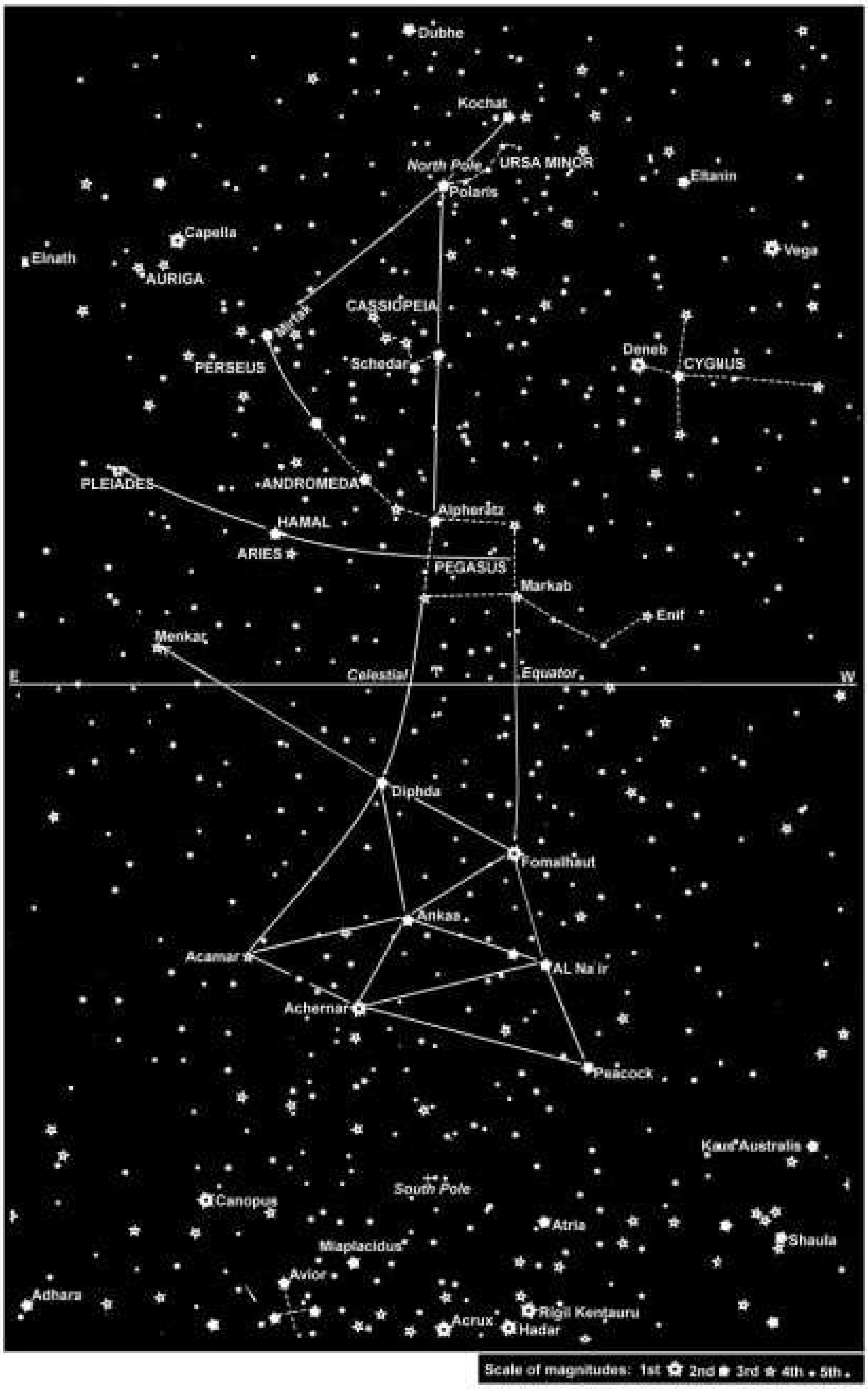
Alphabetical Order						Order of SHA					
Name	No.	Magnitude		SHA	Dec	Name	No.	Magnitude		SHA	Dec
		Visual	S-4					Visual	S-4		
				° ′	° ′					° ′	° ′
Acamar	7	3.2	3.2	315 20	S 40 16	*Markab	57	2.5	2.3	13 41	N 15 16
ACHERNAR	5	0.5	0.1	335 29	S 57 11	FOMALHAUT	56	1.2	1.3	15 27	S 29 34
ACRUX	30	1.3	0.5	173 13	S 63 09	*Al Na'ir	55	1.7	1.8	27 47	S 46 55
*Adhara	19	1.5	1.2	255 15	S 28 59	Enif	54	2.4	4.8	33 50	N 9 55
ALDEBARAN	10	0.9	3.1	290 53	N 16 32	DENEB	53	1.3	1.4	49 33	N 45 19
Alioth	32	1.8	1.5	166 23	N 55 54	Peacock	52	1.9	1.7	53 24	S 56 42
Alkaid	34	1.9	1.5	153 01	N 49 16	ALTAIR	51	0.8	1.0	62 11	N 8 54
*Al Na'ir	55	1.7	1.8	27 47	S 46 55	Nunki	50	2.0	1.9	76 02	S 26 17
*Alnilam	15	1.7	1.3	275 49	S 1 12	VEGA	49	0.0	0.0	80 41	N 38 48
Alphard	25	2.0	4.4	217 59	S 8 42	*Kaus Australis	48	1.9	2.0	83 47	S 34 23
Alphecca	41	2.2	2.1	126 13	N 26 41	*Eltanin	47	2.2	4.6	90 47	N 51 29
Alpheratz	1	2.1	1.8	357 46	N 29 09	Rasalhague	46	2.1	2.2	96 09	N 12 33
ALTAIR	51	0.8	1.0	62 11	N 8 54	Shaula	45	1.6	1.3	96 26	S 37 07
*Ankaa	2	2.4	3.9	353 18	S 42 15	*Sabik	44	2.4	2.5	102 16	S 15 44
ANTARES	42	1.0	3.7	112 30	S 26 27	*Atria	43	1.9	4.1	107 34	S 69 03
ARCTURUS	37	0.0	1.9	145 58	N 19 08	ANTARES	42	1.0	3.7	112 30	S 26 27
*Atria	43	1.9	4.1	107 34	S 69 03	Alphecca	41	2.2	2.1	126 13	N 26 41
*Avior	22	1.9	3.3	234 19	S 59 33	Kochab	40	2.1	4.3	137 20	N 74 07
*Bellatrix	13	1.6	1.2	278 35	N 6 21	*Zubenelgenubi	39	2.8	3.2	137 08	S 16 05
BETELGEUSE	16	0.1-1.2	2.5-3.6	271 04	N 7 24	RIGIL KENT.	38	−0.3	0.9	139 54	S 60 53
CANOPUS	17	−0.7	−0.8	263 57	S 52 42	ARCTURUS	37	0.0	1.9	145 58	N 19 08
CAPELLA	12	0.1	1.3	280 39	N 46 01	*Menkent	36	2.1	3.5	148 11	S 36 25
DENEB	53	1.3	1.4	49 33	N 45 19	*HADAR	35	0.6	0.3	148 52	S 60 25
Denebola	28	2.1	2.2	182 36	N 14 31	Alkaid	34	1.9	1.5	153 01	N 49 16
Diphda	4	2.0	3.6	348 59	S 17 56	SPICA	33	1.0	0.7	158 34	S 11 13
Dubhe	27	1.8	3.4	193 55	N 61 42	Alioth	32	1.8	1.5	166 23	N 55 54
*Elnath	14	1.7	1.4	278 16	N 28 37	*Gacrux	31	1.6	4.1	172 04	S 57 10
*Eltanin	47	2.2	4.6	90 47	N 51 29	ACRUX	30	1.3	0.5	173 13	S 63 09
Enif	54	2.4	4.8	33 50	N 9 55	Gienah	29	2.6	2.5	175 55	S 17 36
FOMALHAUT	56	1.2	1.3	15 27	S 29 34	Denebola	28	2.1	2.2	182 36	N 14 31
*Gacrux	31	1.6	4.1	172 04	S 57 10	Dubhe	27	1.8	3.4	193 55	N 61 42
Gienah	29	2.6	2.5	175 55	S 17 36	REGULUS	26	1.4	1.0	207 46	N 11 55
*HADAR	35	0.6	0.3	148 52	S 60 25	Alphard	25	2.0	4.4	217 59	S 8 42
Hamal	6	2.0	3.8	328 04	N 23 31	Miaplacidus	24	1.7	1.8	221 40	S 69 46
*Kaus Australis	48	1.9	2.0	83 47	S 34 23	Suhail	23	2.2	4.6	222 55	S 43 28
Kochab	40	2.1	4.3	137 20	N 74 07	*Avior	22	1.9	3.3	234 19	S 59 33
*Markab	57	2.5	2.3	13 41	N 15 16	POLLUX	21	1.1	2.5	243 31	N 28 00
Menkar	8	2.5	5.3	314 18	N 4 08	PROCYON	20	0.4	0.8	245 03	N 5 12
*Menkent	36	2.1	3.5	148 11	S 36 25	*Adhara	19	1.5	1.2	255 15	S 28 59
Miaplacidus	24	1.7	1.8	221 40	S 69 46	SIRIUS	18	−1.5	−1.5	258 36	S 16 44
Mirfak	9	1.8	2.4	308 44	N 49 54	CANOPUS	17	−0.7	−0.8	263 57	S 52 42
Nunki	50	2.0	1.9	76 02	S 26 17	BETELGEUSE	16	0.1-1.2	2.5-3.6	271 04	N 7 24
Peacock	52	1.9	1.7	53 24	S 56 42	*Alnilam	15	1.7	1.3	275 49	S 1 12
POLLUX	21	1.1	2.5	243 31	N 28 00	*Elnath	14	1.7	1.4	278 16	N 28 37
PROCYON	20	0.4	0.8	245 03	N 5 12	*Bellatrix	13	1.6	1.2	278 35	N 6 21
Rasalhague	46	2.1	2.2	96 09	N 12 33	CAPELLA	12	0.1	1.3	280 39	N 46 01
REGULUS	26	1.4	1.0	207 46	N 11 55	RIGEL	11	0.1	0.0	281 15	S 8 11
RIGEL	11	0.1	0.0	281 15	S 8 11	ALDEBARAN	10	0.9	3.1	290 53	N 16 32
RIGIL KENT.	38	−0.3	0.9	139 54	S 60 53	Mirfak	9	1.8	2.4	308 44	N 49 54
*Sabik	44	2.4	2.5	102 16	S 15 44	Menkar	8	2.5	5.3	314 18	N 4 08
Schedar	3	2.2	4.1	349 44	N 56 36	Acamar	7	3.2	3.2	315 20	S 40 16
Shaula	45	1.6	1.3	96 26	S 37 07	Hamal	6	2.0	3.8	328 04	N 23 31
SIRIUS	18	−1.5	−1.5	258 36	S 16 44	ACHERNAR	5	0.5	0.1	335 29	S 57 11
SPICA	33	1.0	0.7	158 34	S 11 13	Diphda	4	2.0	3.6	348 59	S 17 56
Suhail	23	2.2	4.6	222 55	S 43 28	Schedar	3	2.2	4.1	349 44	N 56 36
VEGA	49	0.0	0.0	80 41	N 38 48	*Ankaa	2	2.4	3.9	353 18	S 42 15
*Zubenelgenubi	39	2.8	3.2	137 08	S 16 05	Alpheratz	1	2.1	1.8	357 46	N 29 09

The star numbers and names are the same as in *The Air Almanac*.
* Not in tabular pages of Volume 1.

APPENDIX C

(Identification of stars)

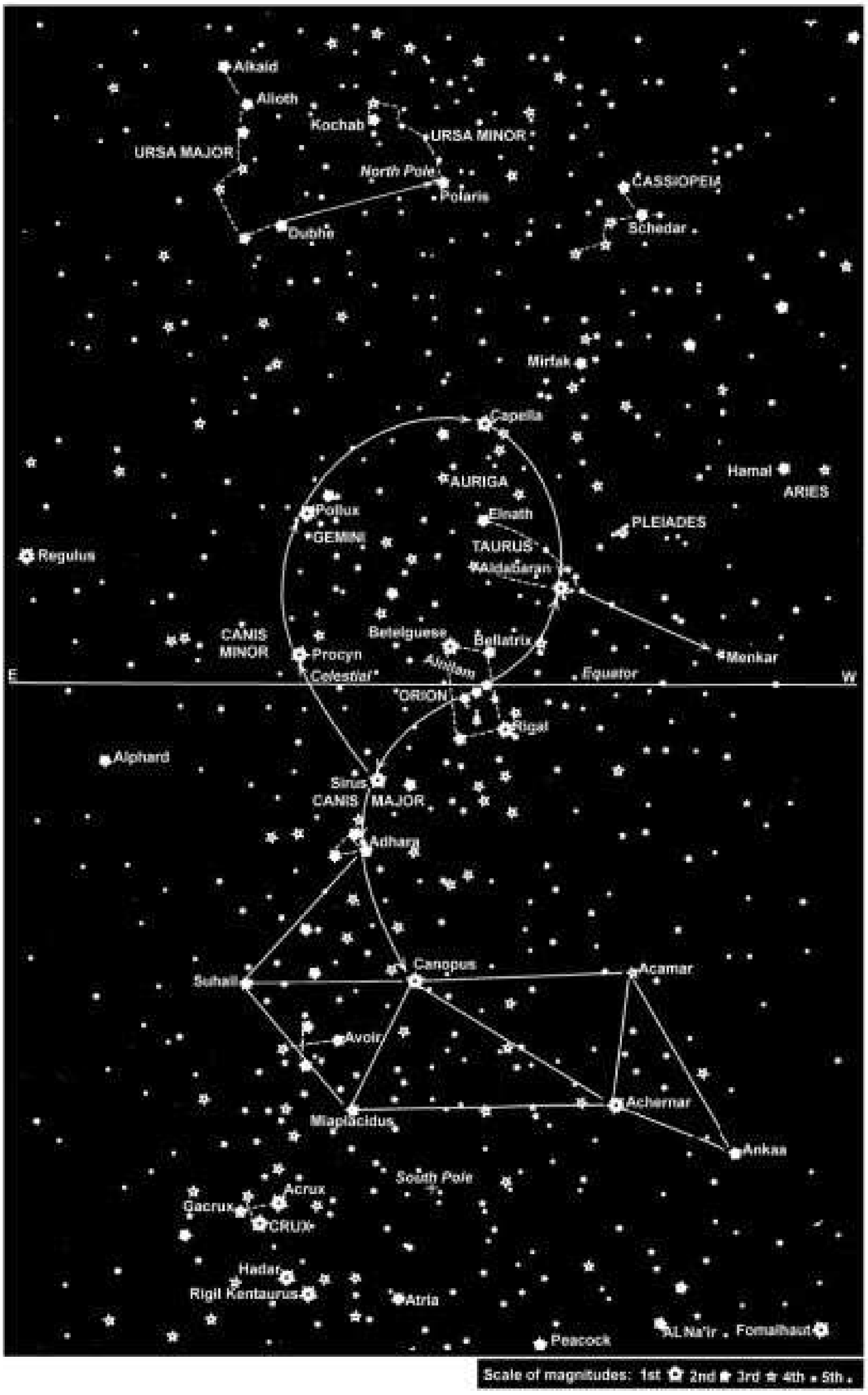
Stars in the vicinity of Pegasus



APPENDIX C

(Identification of stars)

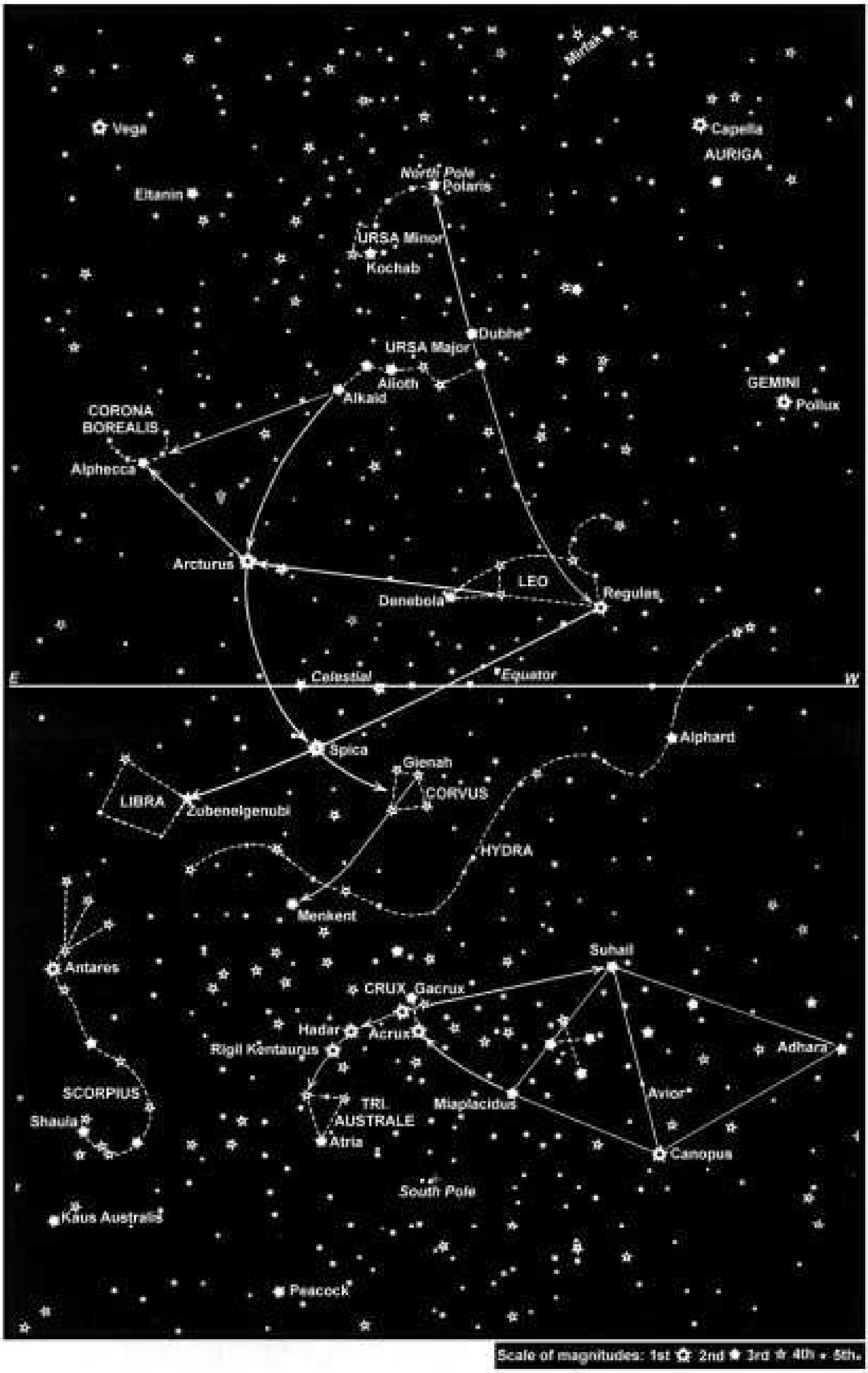
Stars in the vicinity of Orion



APPENDIX C

(Identification of stars)

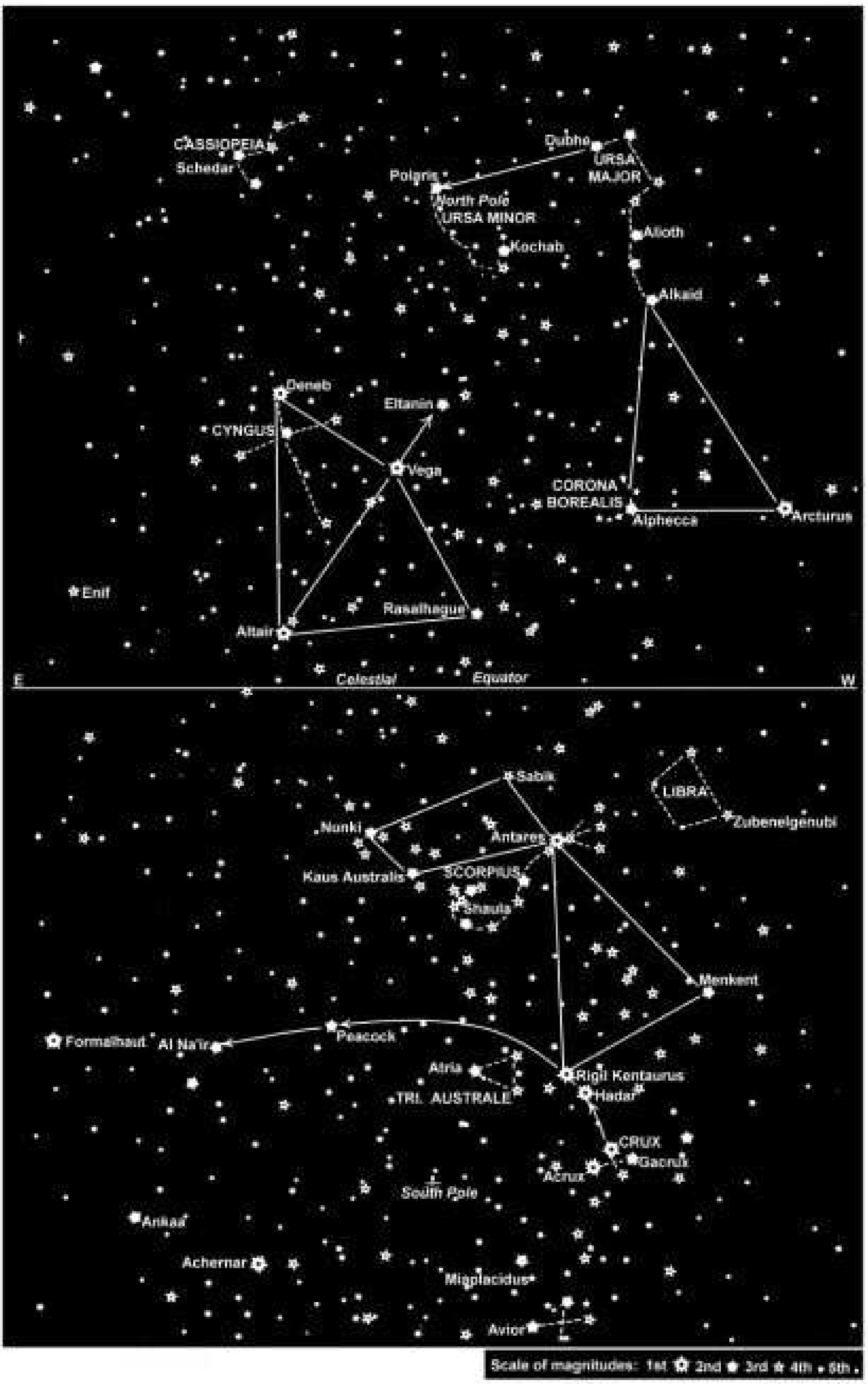
Stars in the vicinity of Ursa Major



APPENDIX C

(Identification of stars)

Stars in the vicinity of Cygnus



APPENDIX D

(GHA of the Aries for the years 2006-2014)

a. GHA ♈ AT 00^h ON THE FIRST DAY OF EACH MONTH

Year	Jan. 1	Feb. 1	Mar. 1	Apr. 1	May 1	June 1	July 1	Aug. 1	Sept. 1	Oct. 1	Nov. 1	Dec. 1
	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
2006	100 30	131 04	158 40	189 13	218 47	249 20	278 55	309 28	340 01	009 35	040 09	069 43
2007	100 16	130 49	158 25	188 59	218 33	249 06	278 40	309 14	339 47	009 21	039 54	069 29
2008	100 02	130 35	159 10	189 44	219 18	249 51	279 25	309 59	340 32	010 06	040 39	070 13
2009	100 47	131 20	158 56	189 29	219 03	249 37	279 11	309 44	340 18	009 52	040 25	069 59
2010	100 33	131 06	158 42	189 15	219 49	249 22	278 57	309 30	340 03	009 37	040 11	069 45
2011	100 18	130 52	158 27	189 01	218 35	249 08	278 42	309 16	339 49	009 23	039 56	069 31
2012	100 04	130 37	159 12	189 45	219 20	249 53	279 27	310 00	340 34	010 08	040 41	070 15
2013	100 49	131 22	158 58	189 31	219 05	249 39	279 13	309 46	340 19	009 53	040 27	070 01
2014	100 34	131 08	158 43	189 17	218 51	249 24	278 58	309 32	340 05	009 39	040 12	069 47

b. INCREMENT OF GHA ♈ FOR DAYS AND HOURS

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
h	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
00	0 00	0 59	1 58	2 57	3 57	4 56	5 55	6 54	7 53	8 52	9 51	10 51	11 50	12 49	13 48	14 47
01	15 02	16 02	17 01	18 00	18 59	19 58	20 57	21 56	22 56	23 55	24 54	25 53	26 52	27 51	28 50	29 50
02	30 05	31 04	32 03	33 02	34 01	35 01	36 00	36 59	37 58	38 57	39 56	40 55	41 55	42 54	43 53	44 52
03	45 07	46 07	47 06	48 05	49 04	50 03	51 02	52 01	53 01	54 00	54 59	55 58	56 57	57 56	58 55	59 54
04	60 10	61 09	62 08	63 07	64 06	65 06	66 05	67 04	68 03	69 02	70 01	71 00	72 00	72 59	73 58	74 57
05	75 12	76 11	77 11	78 10	79 09	80 08	81 07	82 06	83 05	84 05	85 04	86 03	87 02	88 01	89 00	89 59
06	90 15	91 14	92 13	93 12	94 11	95 10	96 10	97 09	98 08	99 07	100 06	101 05	102 04	103 04	104 03	105 02
07	105 17	106 16	107 16	108 15	109 14	110 13	111 12	112 11	113 10	114 09	115 09	116 08	117 07	118 06	119 05	120 04
08	120 20	121 19	122 18	123 17	124 16	125 15	126 15	127 14	128 13	129 12	130 11	131 10	132 09	133 09	134 08	135 07
09	135 22	136 21	137 20	138 20	139 19	140 18	141 17	142 16	143 15	144 14	145 14	146 13	147 12	148 11	149 10	150 09
10	150 25	151 24	152 23	153 22	154 21	155 20	156 19	157 19	158 18	159 17	160 16	161 15	162 14	163 13	164 13	165 12
11	165 27	166 26	167 25	168 25	169 24	170 23	171 22	172 21	173 20	174 19	175 18	176 18	177 17	178 16	179 15	180 14
12	180 30	181 29	182 28	183 27	184 26	185 25	186 24	187 24	188 23	189 22	190 21	191 20	192 19	193 18	194 18	195 17
13	195 32	196 31	197 30	198 29	199 29	200 28	201 27	202 26	203 25	204 24	205 23	206 23	207 22	208 21	209 20	210 19
14	210 34	211 34	212 33	213 32	214 31	215 30	216 29	217 28	218 28	219 27	220 26	221 25	222 24	223 23	224 22	225 22
15	225 37	226 36	227 35	228 34	229 34	230 33	231 32	232 31	233 30	234 29	235 28	236 27	237 27	238 26	239 25	240 24
16	240 39	241 39	242 38	243 37	244 36	245 35	246 34	247 33	248 33	249 32	250 31	251 30	252 29	253 28	254 27	255 27
17	255 42	256 41	257 40	258 39	259 38	260 38	261 37	262 36	263 35	264 34	265 33	266 32	267 32	268 31	269 30	270 29
18	270 44	271 43	272 43	273 42	274 41	275 40	276 39	277 38	278 37	279 37	280 36	281 35	282 34	283 33	284 32	285 31
19	285 47	286 46	287 45	288 44	289 43	290 43	291 42	292 41	293 40	294 39	295 38	296 37	297 36	298 36	299 35	300 34
20	300 49	301 48	302 48	303 47	304 46	305 45	306 44	307 43	308 42	309 42	310 41	311 40	312 39	313 38	314 37	315 36
21	315 52	316 51	317 50	318 49	319 48	320 47	321 47	322 46	323 45	324 44	325 43	326 42	327 41	328 41	329 40	330 39
22	330 54	331 53	332 52	333 52	334 51	335 50	336 49	337 48	338 47	339 46	340 46	341 45	342 44	343 43	344 42	345 41
23	345 57	346 56	347 55	348 54	349 53	350 52	351 52	352 51	353 50	354 49	355 48	356 47	357 46	358 45	359 45	0 44

Day	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
h	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
00	15 46	16 45	17 44	18 44	19 43	20 42	21 41	22 40	23 39	24 38	25 38	26 37	27 36	28 35	29 34	30 33
01	30 49	31 48	32 47	33 46	34 45	35 44	36 44	37 43	38 42	39 41	40 40	41 39	42 38	43 37	44 37	45 36
02	45 51	46 50	47 49	48 49	49 48	50 47	51 46	52 45	53 44	54 43	55 43	56 42	57 41	58 40	59 39	60 38
03	60 54	61 53	62 52	63 51	64 50	65 49	66 48	67 48	68 47	69 46	70 45	71 44	72 43	73 42	74 42	75 41
04	75 56	76 55	77 54	78 53	79 53	80 52	81 51	82 50	83 49	84 48	85 47	86 47	87 46	88 45	89 44	90 43
05	90 59	91 58	92 57	93 56	94 55	95 54	96 53	97 53	98 52	99 51	100 50	101 49	102 48	103 47	104 46	105 46
06	106 01	107 00	107 59	108 58	109 58	110 57	111 56	112 55	113 54	114 53	115 52	116 52	117 51	118 50	119 49	120 48
07	121 03	122 03	123 02	124 01	125 00	125 59	126 58	127 57	128 57	129 56	130 55	131 54	132 53	133 52	134 51	135 51
08	136 06	137 05	138 04	139 03	140 02	141 02	142 01	143 00	143 59	144 58	145 57	146 56	147 56	148 55	149 54	150 53
09	151 08	152 08	153 07	154 06	155 05	156 04	157 03	158 02	159 02	160 01	161 00	161 59	162 58	163 57	164 56	165 55
10	166 11	167 10	168 09	169 08	170 07	171 07	172 06	173 05	174 04	175 03	176 02	177 01	178 01	179 00	179 59	180 58
11	181 13	182 12	183 12	184 11	185 10	186 09	187 08	188 07	189 06	190 06	191 05	192 04	193 03	194 02	195 01	196 00
12	196 16	197 15	198 14	199 13	200 12	201 11	202 11	203 10	204 09	205 08	206 07	207 06	208 05	209 05	210 04	211 03
13	211 18	212 17	213 17	214 16	215 15	216 14	217 13	218 12	219 11	220 11	221 10	222 09	223 08	224 07	225 06	226 05
14	226 21	227 20	228 19	229 18	230 17	231 16	232 16	233 15	234 14	235 13	236 12	237 11	238 10	239 10	240 09	241 08
15	241 23	242 22	243 21	244 21	245 20	246 19	247 18	248 17	249 16	250 15	251 15	252 14	253 13	254 12	255 11	256 10
16	256 26	257 25	258 24	259 23	260 22	261 21	262 20	263 20	264 19	265 18	266 17	267 16	268 15	269 14	270 14	271 13
17	271 28	272 27	273 26	274 26	275 25	276 24	277 23	278 22	279 21	280 20	281 19	282 19	283 18	284 17	285 16	286 15
18	286 31	287 30	288 29	289 28	290 27	291 26	292 25	293 25	294 24	295 23	296 22	297 21	298 20	299 19	300 19	301 18
19	301 33	302 32	303 31	304 30	305 30	306 29	307 28	308 27	309 26	310 25	311 24	312 24	313 23	314 22	315 21	316 20
20	316 36	317 35	318 34	319 33	320 32	321 31	322 30	323 29	324 29	325 28	326 27	327 26	328 25	329 24	330 23	331 23
21	331 38	332 37	333 36	334 35	335 35	336 34	337 33	338 32	339 31	340 30	341 29	342 28	343 28	344 27	345 26	346 25
22	346 40	347 40	348 39	349 38	350 37	351 36	352 35	353 34	354 34	355 33	356 32	357 31	358 30	359 29	0 28	1 28
23	1 43	2 42	3 41	4 40	5 39	6 39	7 38	8 37	9 36	10 35	11 34	12 33	13 33	14 32	15 31	16 30

APPENDIX D

(Increment of GHA of the Aries for minutes and seconds)

c. INCREMENT OF GHA ϒ FOR MINUTES AND SECONDS

	00s	04s	08s	12s	16s	20s	24s	28s		32s	36s	40s	44s	48s	52s	56s	60s	
m	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	m	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	m
00	0 00	0 01	0 02	0 03	0 04	0 05	0 06	0 07	00	0 08	0 09	0 10	0 11	0 12	0 13	0 14	0 15	00
01	0 15	0 16	0 17	0 18	0 19	0 20	0 21	0 22	01	0 23	0 24	0 25	0 26	0 27	0 28	0 29	0 30	01
02	0 30	0 31	0 32	0 33	0 34	0 35	0 36	0 37	02	0 38	0 39	0 40	0 41	0 42	0 43	0 44	0 45	02
03	0 45	0 46	0 47	0 48	0 49	0 50	0 51	0 52	03	0 53	0 54	0 55	0 56	0 57	0 58	0 59	1 00	03
04	1 00	1 01	1 02	1 03	1 04	1 05	1 06	1 07	04	1 08	1 09	1 10	1 11	1 12	1 13	1 14	1 15	04
05	1 15	1 16	1 17	1 18	1 19	1 20	1 21	1 22	05	1 23	1 24	1 25	1 26	1 27	1 28	1 29	1 30	05
06	1 30	1 31	1 32	1 33	1 34	1 35	1 36	1 37	06	1 38	1 39	1 40	1 41	1 42	1 43	1 44	1 45	06
07	1 45	1 46	1 47	1 48	1 49	1 50	1 51	1 52	07	1 53	1 54	1 55	1 56	1 57	1 58	1 59	2 00	07
08	2 00	2 01	2 02	2 03	2 04	2 05	2 06	2 07	08	2 08	2 09	2 10	2 11	2 12	2 13	2 14	2 15	08
09	2 15	2 16	2 17	2 18	2 19	2 20	2 21	2 22	09	2 23	2 24	2 25	2 26	2 27	2 28	2 29	2 30	09
10	2 30	2 31	2 32	2 33	2 34	2 35	2 36	2 37	10	2 38	2 39	2 40	2 41	2 42	2 43	2 44	2 45	10
11	2 45	2 46	2 47	2 48	2 49	2 50	2 51	2 52	11	2 53	2 54	2 55	2 56	2 57	2 58	2 59	3 00	11
12	3 00	3 01	3 02	3 04	3 05	3 06	3 07	3 08	12	3 09	3 10	3 11	3 12	3 13	3 14	3 15	3 16	12
13	3 16	3 17	3 18	3 19	3 20	3 21	3 22	3 23	13	3 24	3 25	3 26	3 27	3 28	3 29	3 30	3 31	13
14	3 31	3 32	3 33	3 34	3 35	3 36	3 37	3 38	14	3 39	3 40	3 41	3 42	3 43	3 44	3 45	3 46	14
15	3 46	3 47	3 48	3 49	3 50	3 51	3 52	3 53	15	3 54	3 55	3 56	3 57	3 58	3 59	4 00	4 01	15
16	4 01	4 02	4 03	4 04	4 05	4 06	4 07	4 08	16	4 09	4 10	4 11	4 12	4 13	4 14	4 15	4 16	16
17	4 16	4 17	4 18	4 19	4 20	4 21	4 22	4 23	17	4 24	4 25	4 26	4 27	4 28	4 29	4 30	4 31	17
18	4 31	4 32	4 33	4 34	4 35	4 36	4 37	4 38	18	4 39	4 40	4 41	4 42	4 43	4 44	4 45	4 46	18
19	4 46	4 47	4 48	4 49	4 50	4 51	4 52	4 53	19	4 54	4 55	4 56	4 57	4 58	4 59	5 00	5 01	19
20	5 01	5 02	5 03	5 04	5 05	5 06	5 07	5 08	20	5 09	5 10	5 11	5 12	5 13	5 14	5 15	5 16	20
21	5 16	5 17	5 18	5 19	5 20	5 21	5 22	5 23	21	5 24	5 25	5 26	5 27	5 28	5 29	5 30	5 31	21
22	5 31	5 32	5 33	5 34	5 35	5 36	5 37	5 38	22	5 39	5 40	5 41	5 42	5 43	5 44	5 45	5 46	22
23	5 46	5 47	5 48	5 49	5 50	5 51	5 52	5 53	23	5 54	5 55	5 56	5 57	5 58	5 59	6 00	6 01	23
24	6 01	6 02	6 03	6 04	6 05	6 06	6 07	6 08	24	6 09	6 10	6 11	6 12	6 13	6 14	6 15	6 16	24
25	6 16	6 17	6 18	6 19	6 20	6 21	6 22	6 23	25	6 24	6 25	6 26	6 27	6 28	6 29	6 30	6 31	25
26	6 31	6 32	6 33	6 34	6 35	6 36	6 37	6 38	26	6 39	6 40	6 41	6 42	6 43	6 44	6 45	6 46	26
27	6 46	6 47	6 48	6 49	6 50	6 51	6 52	6 53	27	6 54	6 55	6 56	6 57	6 58	6 59	7 00	7 01	27
28	7 01	7 02	7 03	7 04	7 05	7 06	7 07	7 08	28	7 09	7 10	7 11	7 12	7 13	7 14	7 15	7 16	28
29	7 16	7 17	7 18	7 19	7 20	7 21	7 22	7 23	29	7 24	7 25	7 26	7 27	7 28	7 29	7 30	7 31	29
30	7 31	7 32	7 33	7 34	7 35	7 36	7 37	7 38	30	7 39	7 40	7 41	7 42	7 43	7 44	7 45	7 46	30
31	7 46	7 47	7 48	7 49	7 50	7 51	7 52	7 53	31	7 54	7 55	7 56	7 57	7 58	7 59	8 00	8 01	31
32	8 01	8 02	8 03	8 04	8 05	8 06	8 07	8 08	32	8 09	8 10	8 11	8 12	8 13	8 14	8 15	8 16	32
33	8 16	8 17	8 18	8 19	8 20	8 21	8 22	8 23	33	8 24	8 25	8 26	8 27	8 28	8 29	8 30	8 31	33
34	8 31	8 32	8 33	8 34	8 35	8 36	8 37	8 38	34	8 39	8 40	8 41	8 42	8 43	8 44	8 45	8 46	34
35	8 46	8 47	8 48	8 49	8 50	8 51	8 52	8 53	35	8 54	8 55	8 56	8 57	8 58	8 59	9 00	9 01	35
36	9 01	9 02	9 03	9 04	9 05	9 06	9 07	9 08	36	9 10	9 11	9 12	9 13	9 14	9 15	9 16	9 17	36
37	9 17	9 18	9 19	9 20	9 21	9 22	9 23	9 24	37	9 25	9 26	9 27	9 28	9 29	9 30	9 31	9 32	37
38	9 32	9 33	9 34	9 35	9 36	9 37	9 38	9 39	38	9 40	9 41	9 42	9 43	9 44	9 45	9 46	9 47	38
39	9 47	9 48	9 49	9 50	9 51	9 52	9 53	9 54	39	9 55	9 56	9 57	9 58	9 59	10 00	10 01	10 02	39
40	10 02	10 03	10 04	10 05	10 06	10 07	10 08	10 09	40	10 10	10 11	10 12	10 13	10 14	10 15	10 16	10 17	40
41	10 17	10 18	10 19	10 20	10 21	10 22	10 23	10 24	41	10 25	10 26	10 27	10 28	10 29	10 30	10 31	10 32	41
42	10 32	10 33	10 34	10 35	10 36	10 37	10 38	10 39	42	10 40	10 41	10 42	10 43	10 44	10 45	10 46	10 47	42
43	10 47	10 48	10 49	10 50	10 51	10 52	10 53	10 54	43	10 55	10 56	10 57	10 58	10 59	11 00	11 01	11 02	43
44	11 02	11 03	11 04	11 05	11 06	11 07	11 08	11 09	44	11 10	11 11	11 12	11 13	11 14	11 15	11 16	11 17	44
45	11 17	11 18	11 19	11 20	11 21	11 22	11 23	11 24	45	11 25	11 26	11 27	11 28	11 29	11 30	11 31	11 32	45
46	11 32	11 33	11 34	11 35	11 36	11 37	11 38	11 39	46	11 40	11 41	11 42	11 43	11 44	11 45	11 46	11 47	46
47	11 47	11 48	11 49	11 50	11 51	11 52	11 53	11 54	47	11 55	11 56	11 57	11 58	11 59	12 00	12 01	12 02	47
48	12 02	12 03	12 04	12 05	12 06	12 07	12 08	12 09	48	12 10	12 11	12 12	12 13	12 14	12 15	12 16	12 17	48
49	12 17	12 18	12 19	12 20	12 21	12 22	12 23	12 24	49	12 25	12 26	12 27	12 28	12 29	12 30	12 31	12 32	49
50	12 32	12 33	12 34	12 35	12 36	12 37	12 38	12 39	50	12 40	12 41	12 42	12 43	12 44	12 45	12 46	12 47	50
51	12 47	12 48	12 49	12 50	12 51	12 52	12 53	12 54	51	12 55	12 56	12 57	12 58	12 59	13 00	13 01	13 02	51
52	13 02	13 03	13 04	13 05	13 06	13 07	13 08	13 09	52	13 10	13 11	13 12	13 13	13 14	13 15	13 16	13 17	52
53	13 17	13 18	13 19	13 20	13 21	13 22	13 23	13 24	53	13 25	13 26	13 27	13 28	13 29	13 30	13 31	13 32	53
54	13 32	13 33	13 34	13 35	13 36	13 37	13 38	13 39	54	13 40	13 41	13 42	13 43	13 44	13 45	13 46	13 47	54
55	13 47	13 48	13 49	13 50	13 51	13 52	13 53	13 54	55	13 55	13 56	13 57	13 58	13 59	14 00	14 01	14 02	55
56	14 02	14 03	14 04	14 05	14 06	14 07	14 08	14 09	56	14 10	14 11	14 12	14 13	14 14	14 15	14 16	14 17	56
57	14 17	14 18	14 19	14 20	14 21	14 22	14 23	14 24	57	14 25	14 26	14 27	14 28	14 29	14 30	14 31	14 32	57
58	14 32	14 33	14 34	14 35	14 36	14 37	14 38	14 39	58	14 40	14 41	14 42	14 43	14 44	14 45	14 46	14 47	58
59	14 47	14 48	14 49	14 50	14 51	14 52	14 53	14 54	59	14 55	14 56	14 57	14 58	14 59	15 00	15 01	15 02	59

Example. The value of GHAϒ for 2012 August 17 at $05^h\ 11^m\ 41^s$ UT is (a) 310° 00′ + (b) 090° 59′ + (c) 002° 55′ = 043° 54′.

APPENDIX E

(GHA and declination of the Sun)

OT 00h	JAN E	JAN Dec.		FEB E	FEB Dec.		MAR E	MAR Dec.		APR E	APR Dec.	
d	° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′	
1	4 12	S 23 03	5	1 38	S 17 16	17	1 52	S 7 49	23	3 58	N 4 19	23
2	4 05	22 58	5	1 36	16 59	18	1 55	7 26	23	4 02	4 42	23
3	3 58	22 53	6	1 34	16 41	17	1 58	7 03	23	4 07	5 05	23
4	3 51	22 47	7	1 32	16 24	18	2 01	6 40	23	4 11	5 28	23
5	3 44	22 40	6	1 31	16 06	18	2 05	6 17	23	4 16	5 51	23
6	3 37	S 22 34	7	1 30	S 15 48	19	2 08	S 5 54	24	4 20	N 6 14	22
7	3 31	22 27	8	1 29	15 29	18	2 11	5 30	23	4 24	6 36	23
8	3 24	22 19	8	1 28	15 11	19	2 15	5 07	23	4 29	6 59	22
9	3 18	22 11	9	1 27	14 52	20	2 19	4 44	24	4 33	7 21	23
10	3 12	22 02	8	1 27	14 32	19	2 22	4 20	23	4 37	7 44	22
11	3 06	S 21 54	10	1 26	S 14 13	20	2 26	S 3 57	24	4 41	N 8 06	22
12	3 00	21 44	10	1 26	13 53	20	2 30	3 33	23	4 45	8 28	22
13	2 54	21 34	10	1 27	13 33	20	2 34	3 10	24	4 49	8 50	22
14	2 48	21 24	10	1 27	13 13	20	2 38	2 46	24	4 53	9 12	21
15	2 43	21 14	11	1 28	12 53	21	2 43	2 22	23	4 56	9 33	22
16	2 38	S 21 03	12	1 28	S 12 32	21	2 47	S 1 59	24	5 00	N 9 55	21
17	2 32	20 51	12	1 29	12 11	21	2 51	1 35	24	5 04	10 16	21
18	2 28	20 39	12	1 30	11 50	21	2 55	1 11	24	5 07	10 37	21
19	2 23	20 27	12	1 31	11 29	21	3 00	0 47	23	5 10	10 58	21
20	2 18	20 15	13	1 33	11 08	22	3 04	S 0 24	24	5 14	11 19	20
21	2 14	S 20 02	14	1 34	S 10 46	21	3 09	N 0 00	24	5 17	N 11 39	21
22	2 09	19 48	13	1 36	10 25	22	3 13	0 24	23	5 20	12 00	20
23	2 05	19 35	14	1 38	10 03	22	3 17	0 47	24	5 23	12 20	20
24	2 02	19 21	15	1 40	9 41	22	3 22	1 11	24	5 26	12 40	20
25	1 58	19 06	15	1 42	9 19	23	3 26	1 35	23	5 28	13 00	19
26	1 54	S 18 51	15	1 45	S 8 56	22	3 31	N 1 58	24	5 31	N 13 19	20
27	1 51	18 36	15	1 47	8 34	23	3 36	2 22	23	5 33	13 39	19
28	1 48	18 21	16	1 50	8 11	22	3 40	2 45	24	5 36	13 58	19
29	1 45	18 05	16	1 52	7 49	23	3 45	3 09	23	5 38	14 17	18
30	1 42	17 49	16				3 49	3 32	23	5 40	14 35	19
31	1 40	S 17 33	17				3 54	N 3 55	24			

OT 00h	MAY E	MAY Dec.		JUN E	JUN Dec.		JUL E	JUL Dec.		AUG E	AUG Dec.	
d	° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′	
1	5 42	N 14 54	18	5 35	N 21 58	8	4 05	N 23 09	4	3 24	N 18 10	15
2	5 44	15 12	18	5 32	22 06	8	4 02	23 05	5	3 25	17 55	16
3	5 46	15 30	18	5 30	22 14	8	3 59	23 00	5	3 26	17 39	15
4	5 47	15 48	17	5 28	22 22	7	3 56	22 55	5	3 28	17 24	16
5	5 49	16 05	17	5 25	22 29	6	3 54	22 50	5	3 29	17 08	17
6	5 50	N 16 22	17	5 22	N 22 35	6	3 51	N 22 45	6	3 31	N 16 51	16
7	5 51	16 39	17	5 20	22 41	6	3 48	22 39	7	3 32	16 35	17
8	5 52	16 56	16	5 17	22 47	6	3 46	22 32	7	3 34	16 18	17
9	5 53	17 12	16	5 14	22 53	5	3 44	22 25	7	3 36	16 01	17
10	5 54	17 28	16	5 11	22 58	4	3 42	22 18	7	3 38	15 44	17
11	5 54	N 17 44	15	5 08	N 23 02	5	3 39	N 22 11	8	3 40	N 15 27	18
12	5 55	17 59	15	5 05	23 07	3	3 37	22 03	8	3 43	15 09	18
13	5 55	18 14	15	5 02	23 10	4	3 36	21 55	9	3 45	14 51	19
14	5 55	18 29	14	4 59	23 14	3	3 34	21 46	9	3 48	14 32	18
15	5 55	18 43	15	4 56	23 17	2	3 32	21 37	10	3 51	14 14	19
16	5 55	N 18 58	13	4 53	N 23 19	3	3 31	N 21 27	9	3 54	N 13 55	19
17	5 55	19 11	14	4 50	23 22	1	3 29	21 18	11	3 57	13 36	19
18	5 54	19 25	13	4 46	23 23	2	3 28	21 07	10	4 00	13 17	19
19	5 54	19 38	13	4 43	23 25	1	3 27	20 57	11	4 03	12 58	20
20	5 53	19 51	13	4 40	23 26	0	3 26	20 46	11	4 07	12 38	19
21	5 52	N 20 04	12	4 36	N 23 26	0	3 25	N 20 35	12	4 10	N 12 19	20
22	5 51	20 16	12	4 33	23 26	0	3 24	20 23	12	4 14	11 59	21
23	5 50	20 28	11	4 30	23 26	1	3 23	20 11	12	4 18	11 38	20
24	5 49	20 39	11	4 27	23 25	1	3 23	19 59	12	4 21	11 18	20
25	5 48	20 50	11	4 23	23 24	1	3 23	19 47	13	4 25	10 58	21
26	5 46	N 21 01	11	4 20	N 23 23	2	3 22	N 19 34	13	4 29	N 10 37	21
27	5 44	21 12	10	4 17	23 21	3	3 22	19 21	14	4 34	10 16	21
28	5 43	21 22	9	4 14	23 18	3	3 22	19 07	14	4 38	9 55	21
29	5 41	21 31	10	4 11	23 15	3	3 23	18 53	14	4 42	9 34	21
30	5 39	21 41	9	4 08	23 12	3	3 23	18 39	15	4 47	9 13	22
31	5 37	N 21 50	8				3 24	N 18 24	14	4 51	N 8 51	21

OT 00h	SEP E	SEP Dec.		OCT E	OCT Dec.		NOV E	NOV Dec.		DEC E	DEC Dec.		OT 00h
d	° ′	° ′		° ′	° ′		° ′	° ′		° ′	° ′		d
1	4 56	N 8 30	22	7 31	S 2 57	24	9 06	S 14 14	19	7 49	S 21 42	10	1
2	5 01	8 08	22	7 36	3 21	23	9 06	14 33	19	7 44	21 52	9	2
3	5 06	7 46	22	7 41	3 44	23	9 06	14 52	19	7 38	22 01	8	3
4	5 11	7 24	22	7 45	4 07	23	9 06	15 11	19	7 32	22 09	8	4
5	5 16	7 02	22	7 50	4 30	23	9 06	15 30	18	7 26	22 17	8	5
6	5 21	N 6 40	23	7 55	S 4 53	23	9 06	S 15 48	18	7 20	S 22 25	7	6
7	5 26	6 17	22	7 59	5 16	23	9 05	16 06	18	7 14	22 32	7	7
8	5 31	5 55	23	8 03	5 39	23	9 05	16 24	17	7 07	22 39	6	8
9	5 36	5 32	22	8 08	6 02	23	9 04	16 41	17	7 01	22 45	6	9
10	5 41	5 10	23	8 12	6 25	23	9 02	16 58	17	6 54	22 51	6	10
11	5 46	N 4 47	23	8 16	S 6 48	22	9 01	S 17 15	17	6 47	S 22 57	5	11
12	5 52	4 24	23	8 20	7 10	23	8 59	17 32	16	6 40	23 02	4	12
13	5 57	4 01	23	8 23	7 33	22	8 58	17 48	16	6 33	23 06	4	13
14	6 02	3 38	23	8 27	7 55	23	8 55	18 04	16	6 26	23 10	4	14
15	6 08	3 15	23	8 31	8 18	22	8 53	18 20	15	6 19	23 14	3	15
16	6 13	N 2 52	23	8 34	S 8 40	22	8 51	S 18 35	15	6 12	S 23 17	3	16
17	6 18	2 29	23	8 37	9 02	22	8 48	18 50	15	6 05	23 20	2	17
18	6 24	2 06	23	8 40	9 24	22	8 45	19 05	14	5 57	23 22	2	18
19	6 29	1 43	24	8 43	9 46	21	8 42	19 19	14	5 50	23 24	1	19
20	6 34	1 19	23	8 46	10 07	22	8 39	19 33	14	5 42	23 25	1	20
21	6 40	N 0 56	23	8 48	S 10 29	21	8 35	S 19 47	13	5 35	S 23 26	0	21
22	6 45	0 33	24	8 51	10 50	22	8 31	20 00	13	5 28	23 26	0	22
23	6 50	N 0 09	23	8 53	11 12	21	8 27	20 13	12	5 20	23 26	0	23
24	6 55	S 0 14	23	8 55	11 33	20	8 23	20 25	13	5 13	23 26	2	24
25	7 01	0 37	24	8 57	11 53	21	8 19	20 38	11	5 05	23 24	1	25
26	7 06	S 1 01	23	8 59	S 12 14	21	8 14	S 20 49	12	4 58	S 23 23	2	26
27	7 11	1 24	23	9 01	12 35	20	8 10	21 01	11	4 50	23 21	3	27
28	7 16	1 47	24	9 02	12 55	20	8 05	21 12	10	4 43	23 18	2	28
29	7 21	2 11	23	9 03	13 15	20	8 00	21 22	11	4 36	23 16	4	29
30	7 26	2 34	23	9 04	13 35	20	7 55	21 33	9	4 28	23 12	4	30
31				9 05	S 13 55	19				4 21	S 23 08	4	31

a. Corr. to GMT

Year	Corr.	Year	Corr.	Year	Corr.
	h		h		h
1981	+ 7	1993	+ 9	2005	+11
1982	+ 1	1994	+ 4	2006	+ 6
1983	- 5	1995	- 2	2007	0
1984	-10	1996	- 8	2008	- 6
1984	+14 *	1996	+16 *	2008	+18 *
1985	+ 8	1997	+10	2009	+12
1986	+ 2	1998	+ 4	2010	+ 6
1987	- 4	1999	- 2	2011	+ 1
1988	-10	2000	- 8	2012	- 5
1988	+14 *	2000	+16 *	2012	+19 *
1989	+ 9	2001	+10	2013	+13
1990	+ 3	2002	+ 5	2014	+ 7
1991	- 3	2003	- 1	2015	+ 1
1992	- 9	2004	- 7	2016	- 5
1992	+15 *	2004	+17 *	2016	+19 *

* After Feb. 29

b. Interpolation for Hours of OT

Diff.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
h	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′	′
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2
3	0	0	0	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3	3	3	3
4	0	0	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	3	4	4	4	4
5	0	0	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5
6	0	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5	5	5	5	6	6	6
7	0	1	1	1	1	2	2	2	3	3	3	3	4	4	4	5	5	5	6	6	6	6	7	7
8	0	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	7	8	8
9	0	1	1	2	2	2	3	3	3	4	4	5	5	5	6	6	6	7	7	8	8	8	9	9
10	0	1	1	2	2	3	3	3	4	4	5	5	5	6	6	7	7	8	8	8	9	9	10	10
11	0	1	1	2	2	3	3	4	4	5	5	6	6	6	7	7	8	8	9	9	10	10	11	11
12	1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9	10	10	11	11	12	12
13	1	1	2	2	3	3	4	4	5	5	6	7	7	8	8	9	9	10	10	11	11	12	12	13
14	1	1	2	2	3	4	4	5	5	6	6	7	7	8	9	9	10	11	11	12	12	13	13	14
15	1	1	2	3	3	4	4	5	6	6	7	8	8	9	9	10	11	11	12	13	13	14	14	15
16	1	1	2	3	3	4	5	5	6	7	7	8	9	9	10	11	11	12	13	13	14	15	15	16
17	1	1	2	3	4	4	5	6	6	7	8	9	9	10	11	11	12	13	13	14	15	16	16	17
18	1	2	2	3	4	5	5	6	7	8	8	9	10	11	11	12	13	14	14	15	16	17	17	18
19	1	2	2	3	4	5	6	6	7	8	9	10	10	11	12	13	13	14	15	16	17	17	18	19
20	1	2	3	3	4	5	6	7	8	8	9	10	11	12	13	13	14	15	16	17	18	18	19	20
21	1	2	3	4	4	5	6	7	8	9	10	11	11	12	13	14	15	16	17	18	18	19	20	21
22	1	2	3	4	5	6	6	7	8	9	10	11	12	13	14	15	16	17	17	18	19	20	21	22
23	1	2	3	4	5	6	7	8	9	10	11	12	12	13	14	15	16	17	18	19	20	21	22	23

APPENDIX E

(GHA and declination of the Sun)

c. Hours and Tens of Minutes of GMT

h	00m °	00m ′	10m °	10m ′	20m °	20m ′	30m °	30m ′	40m °	40m ′	50m °	50m ′
00	175	00	177	30	180	00	182	30	185	00	187	30
01	190	00	192	30	195	00	197	30	200	00	202	30
02	205	00	207	30	210	00	212	30	215	00	217	30
03	220	00	222	30	225	00	227	30	230	00	232	30
04	235	00	237	30	240	00	242	30	245	00	247	30
05	250	00	252	30	255	00	257	30	260	00	262	30
06	265	00	267	30	270	00	272	30	275	00	277	30
07	280	00	282	30	285	00	287	30	290	00	292	30
08	295	00	297	30	300	00	302	30	305	00	307	30
09	310	00	312	30	315	00	317	30	320	00	322	30
10	325	00	327	30	330	00	332	30	335	00	337	30
11	340	00	342	30	345	00	347	30	350	00	352	30
12	355	00	357	30	0	00	2	30	5	00	7	30
13	10	00	12	30	15	00	17	30	20	00	22	30
14	25	00	27	30	30	00	32	30	35	00	37	30
15	40	00	42	30	45	00	47	30	50	00	52	30
16	55	00	57	30	60	00	62	30	65	00	67	30
17	70	00	72	30	75	00	77	30	80	00	82	30
18	85	00	87	30	90	00	92	30	95	00	97	30
19	100	00	102	30	105	00	107	30	110	00	112	30
20	115	00	117	30	120	00	122	30	125	00	127	30
21	130	00	132	30	135	00	137	30	140	00	142	30
22	145	00	147	30	150	00	152	30	155	00	157	30
23	160	00	162	30	165	00	167	30	170	00	172	30

d. Minutes and Seconds of GMT (in critical cases ascend)

m s	° ′	m s	° ′	m s	° ′	m s	° ′	m s	° ′	m s	° ′
00 00	0 00	01 37	0 25	03 17	0 50	04 57	1 15	06 37	1 40	08 17	2 05
01	0 01	41	0 26	21	0 51	05 01	1 16	41	1 41	21	2 06
05	0 02	45	0 27	25	0 52	05	1 17	45	1 42	25	2 07
09	0 03	49	0 28	29	0 53	09	1 18	49	1 43	29	2 08
13	0 04	53	0 29	33	0 54	13	1 19	53	1 44	33	2 09
17	0 05	01 57	0 30	37	0 55	17	1 20	06 57	1 45	37	2 10
21	0 06	02 01	0 31	41	0 56	21	1 21	07 01	1 46	41	2 11
25	0 07	05	0 32	45	0 57	25	1 22	05	1 47	45	2 12
29	0 08	09	0 33	49	0 58	29	1 23	09	1 48	49	2 13
33	0 09	13	0 34	53	0 59	33	1 24	13	1 49	53	2 14
37	0 10	17	0 35	03 57	1 00	37	1 25	17	1 50	08 57	2 15
41	0 11	21	0 36	04 01	1 01	41	1 26	21	1 51	09 01	2 16
45	0 12	25	0 37	05	1 02	45	1 27	25	1 52	05	2 17
49	0 13	29	0 38	09	1 03	49	1 28	29	1 53	09	2 18
53	0 14	33	0 39	13	1 04	53	1 29	33	1 54	13	2 19
00 57	0 15	37	0 40	17	1 05	05 57	1 30	37	1 55	17	2 20
01 01	0 16	41	0 41	21	1 06	06 01	1 31	41	1 56	21	2 21
05	0 17	45	0 42	25	1 07	05	1 32	45	1 57	25	2 22
09	0 18	49	0 43	29	1 08	09	1 33	49	1 58	29	2 23
13	0 19	53	0 44	33	1 09	13	1 34	53	1 59	33	2 24
17	0 20	02 57	0 45	37	1 10	17	1 35	07 57	2 00	37	2 25
21	0 21	03 01	0 46	41	1 11	21	1 36	08 01	2 01	41	2 26
25	0 22	05	0 47	45	1 12	25	1 37	05	2 02	45	2 27
29	0 23	09	0 48	49	1 13	29	1 38	09	2 03	49	2 28
33	0 24	13	0 49	53	1 14	33	1 39	13	2 04	53	2 29
37	0 25	17	0 50	04 57	1 15	37	1 40	17	2 05	09 57	2 30
01 41		03 21		05 01		06 41		08 21		10 00	

APPENDIX F

(Formulae for plane trigonometry)

Darstellung einer Funktion durch eine andere Funktion desselben Winkels*:

$$\sin\alpha = \sqrt{1-\cos^2\alpha} = \frac{\operatorname{tg}\alpha}{\sqrt{1+\operatorname{tg}^2\alpha}} = \frac{1}{\sqrt{1+\operatorname{ctg}^2\alpha}} = \frac{\sqrt{\operatorname{sc}^2\alpha-1}}{\operatorname{sc}\alpha} = \frac{1}{\csc\alpha},$$

$$\cos\alpha = \sqrt{1-\sin^2\alpha} = \frac{1}{\sqrt{1+\operatorname{tg}^2\alpha}} = \frac{\operatorname{ctg}\alpha}{\sqrt{1+\operatorname{ctg}^2\alpha}} = \frac{1}{\operatorname{sc}\alpha} = \frac{\sqrt{\csc^2\alpha-1}}{\csc\alpha},$$

$$\operatorname{tg}\alpha = \frac{\sin\alpha}{\sqrt{1-\sin^2\alpha}} = \frac{\sqrt{1-\cos^2\alpha}}{\cos\alpha} = \frac{1}{\operatorname{ctg}\alpha} = \sqrt{\operatorname{sc}^2\alpha-1} = \frac{1}{\sqrt{\csc^2\alpha-1}},$$

$$\operatorname{ctg}\alpha = \frac{\sqrt{1-\sin^2\alpha}}{\sin\alpha} = \frac{\cos\alpha}{\sqrt{1-\cos^2\alpha}} = \frac{1}{\operatorname{tg}\alpha} = \frac{1}{\sqrt{\operatorname{sc}^2\alpha-1}} = \sqrt{\csc^2\alpha-1}.$$

Funktionen der Summe und der Differenz zweier Winkel:

$$\sin(\alpha\pm\beta) = \sin\alpha\cos\beta \pm \cos\alpha\sin\beta,\quad \cos(\alpha\pm\beta) = \cos\alpha\cos\beta \mp \sin\alpha\sin\beta,$$

$$\operatorname{tg}(\alpha\pm\beta) = \frac{\operatorname{tg}\alpha \pm \operatorname{tg}\beta}{1\mp\operatorname{tg}\alpha\operatorname{tg}\beta},\quad \operatorname{ctg}(\alpha\pm\beta) = \frac{\operatorname{ctg}\alpha\operatorname{ctg}\beta\mp 1}{\operatorname{ctg}\beta\pm\operatorname{ctg}\alpha};$$

$$\sin(\alpha+\beta+\gamma) = \sin\alpha\cos\beta\cos\gamma + \cos\alpha\sin\beta\cos\gamma + \cos\alpha\cos\beta\sin\gamma - \sin\alpha\sin\beta\sin\gamma,$$

$$\cos(\alpha+\beta+\gamma) = \cos\alpha\cos\beta\cos\gamma - \sin\alpha\sin\beta\cos\gamma - \sin\alpha\cos\beta\sin\gamma - \cos\alpha\sin\beta\sin\gamma.$$

Funktionen für Winkelvielfache:

$$\sin 2\alpha = 2\sin\alpha\cos\alpha,\qquad \sin 3\alpha = 3\sin\alpha - 4\sin^3\alpha,$$

$$\cos 2\alpha = \cos^2\alpha - \sin^2\alpha;\qquad \cos 3\alpha = 4\cos^3\alpha - 3\cos\alpha;$$

$$\sin 4\alpha = 8\cos^3\alpha\sin\alpha - 4\cos\alpha\sin\alpha,$$

$$\cos 4\alpha = 8\cos^4\alpha - 8\cos^2\alpha + 1;$$

$$\operatorname{tg}2\alpha = \frac{2\operatorname{tg}\alpha}{1-\operatorname{tg}^2\alpha},\quad \operatorname{tg}3\alpha = \frac{3\operatorname{tg}\alpha-\operatorname{tg}^3\alpha}{1-3\operatorname{tg}^2\alpha},\quad \operatorname{tg}4\alpha = \frac{4\operatorname{tg}\alpha-4\operatorname{tg}^3\alpha}{1-6\operatorname{tg}^2\alpha+\operatorname{tg}^4\alpha},$$

$$\operatorname{ctg}2\alpha = \frac{\operatorname{ctg}^2\alpha-1}{2\operatorname{ctg}\alpha},\quad \operatorname{ctg}3\alpha = \frac{\operatorname{ctg}^3\alpha-3\operatorname{ctg}\alpha}{3\operatorname{ctg}^2\alpha-1},\quad \operatorname{ctg}4\alpha = \frac{\operatorname{ctg}^4\alpha-6\operatorname{ctg}^2\alpha+1}{4\operatorname{ctg}^3\alpha-4\operatorname{ctg}\alpha}.$$

$\sin n\alpha$ und $\cos n\alpha$ für große n ermittelt man vorteilhaft unter Verwendung der Moivreschen Formel für komplexe Zahlen,

$$\cos n\alpha + i\sin n\alpha = (\cos\alpha + i\sin\alpha)^n = \cos^n\alpha + i\,n\cos^{n-1}\alpha\sin\alpha$$
$$- \binom{n}{2}\cos^{n-2}\alpha\sin^2\alpha - i\binom{n}{3}\cos^{n-3}\alpha\sin^3\alpha + \binom{n}{4}\cos^{n-4}\alpha\sin^4\alpha + \cdots,$$

woraus

$$\cos n\alpha = \cos^n\alpha - \binom{n}{2}\cos^{n-2}\alpha\sin^2\alpha + \binom{n}{4}\cos^{n-4}\alpha\sin^4\alpha - \binom{n}{6}\cos^{n-6}\alpha\sin^6\alpha + \cdots,$$

$$\sin n\alpha = n\cos^{n-1}\alpha\sin\alpha - \binom{n}{3}\cos^{n-3}\alpha\sin^3\alpha + \binom{n}{5}\cos^{n-5}\alpha\sin^5\alpha - \ldots$$

folgt.

---

* In diesen Formeln ist der Wurzel das positive oder negative Vorzeichen zu geben, je nachdem, in welchem Quadranten der Winkel liegt.

** $\binom{n}{m}$ sind die Binomialkoeffizienten (vgl. S. 140).

APPENDIX F

(Formulae for plane trigonometry cont.)

Funktionen des halben Winkels:*

$$\sin\frac{\alpha}{2} = \sqrt{\frac{1}{2}(1-\cos\alpha)}, \quad \operatorname{tg}\frac{\alpha}{2} = \sqrt{\frac{1-\cos\alpha}{1+\cos\alpha}} = \frac{1-\cos\alpha}{\sin\alpha} = \frac{\sin\alpha}{1+\cos\alpha},$$

$$\cos\frac{\alpha}{2} = \sqrt{\frac{1}{2}(1+\cos\alpha)}, \quad \operatorname{ctg}\frac{\alpha}{2} = \sqrt{\frac{1+\cos\alpha}{1-\cos\alpha}} = \frac{1+\cos\alpha}{\sin\alpha} = \frac{\sin\alpha}{1-\cos\alpha},$$

Summe und Differenz zweier Funktionen:

$$\sin\alpha + \sin\beta = 2\sin\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}, \quad \operatorname{tg}\alpha \pm \operatorname{tg}\beta = \frac{\sin(\alpha\pm\beta)}{\cos\alpha\cos\beta},$$

$$\sin\alpha - \sin\beta = 2\cos\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}, \quad \operatorname{ctg}\alpha \pm \operatorname{ctg}\beta = \pm\frac{\sin(\alpha\pm\beta)}{\sin\alpha\sin\beta},$$

$$\cos\alpha + \cos\beta = 2\cos\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}, \quad \operatorname{tg}\alpha + \operatorname{ctg}\beta = \frac{\cos(\alpha-\beta)}{\cos\alpha\sin\beta},$$

$$\cos\alpha - \cos\beta = -2\sin\frac{\alpha+\beta}{2}\sin\frac{\alpha-\beta}{2}, \quad \operatorname{ctg}\alpha - \operatorname{tg}\beta = \frac{\cos(\alpha+\beta)}{\sin\alpha\cos\beta}.$$

Produkte von Funktionen:

$$\sin\alpha\sin\beta = \frac{1}{2}[\cos(\alpha-\beta) - \cos(\alpha+\beta)],$$

$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha-\beta) + \cos(\alpha+\beta)],$$

$$\sin\alpha\cos\beta = \frac{1}{2}[\sin(\alpha-\beta) + \sin(\alpha+\beta)],$$

$$\sin\alpha\sin\beta\sin\gamma = \frac{1}{4}[\sin(\alpha+\beta-\gamma) + \sin(\beta+\gamma-\alpha) + \sin(\gamma+\alpha-\beta) - \sin(\alpha+\beta+\gamma)],$$

$$\sin\alpha\cos\beta\cos\gamma = \frac{1}{4}[\sin(\alpha+\beta-\gamma) - \sin(\beta+\gamma-\alpha) + \sin(\gamma+\alpha-\beta) + \sin(\alpha+\beta+\gamma)],$$

$$\sin\alpha\sin\beta\cos\gamma = \frac{1}{4}[-\cos(\alpha+\beta-\gamma) + \cos(\beta+\gamma-\alpha) + \cos(\gamma+\alpha-\beta) - \cos(\alpha+\beta+\gamma)],$$

$$\cos\alpha\cos\beta\cos\gamma = \frac{1}{4}[\cos(\alpha+\beta-\gamma) + \cos(\beta+\gamma-\alpha) + \cos(\gamma+\alpha-\beta) + \cos(\alpha+\beta+\gamma)].$$

Potenzen von Funktionen:

$$\sin^2\alpha = \frac{1}{2}(1-\cos 2\alpha), \quad \sin^3\alpha = \frac{1}{4}(3\sin\alpha - \sin 3\alpha),$$

$$\cos^2\alpha = \frac{1}{2}(1+\cos 2\alpha), \quad \cos^3\alpha = \frac{1}{4}(\cos 3\alpha + 3\cos\alpha),$$

$$\sin^4\alpha = \frac{1}{8}(\cos 4\alpha - 4\cos 2\alpha + 3),$$

$$\cos^4\alpha = \frac{1}{8}(\cos 4\alpha + 4\cos 2\alpha + 3).$$

Zur Berechnung von $\sin^n\alpha$ und $\cos^n\alpha$ bei großem n kann man nacheinander die Formeln für $\cos n\alpha$ und $\sin n\alpha$ von S. 156 verwenden.

APPENDIX G

(Weather patterns / information / Interpretation)

To foresee the weather, navigators mainly rely on information provided by outside sources. These are forecasts provided by wireless internet connections, Navtex receivers, or shipping forecasts available at short wave or VHF transmitters. Additionally navigators can extract valuable information from the clouds, the run of the see and from the indication of traditional aneroid barometers.

A basic guide for the understanding of the weather at north latitudes looks as follows.

- Winds circulate around high and low pressure systems
- Lows (depressions) tend to move eastwards
- Wind doesn't blow in and out of pressure systems. It streams clockwise around highs and anticlockwise around lows, running more or less along the isobars on the weather map

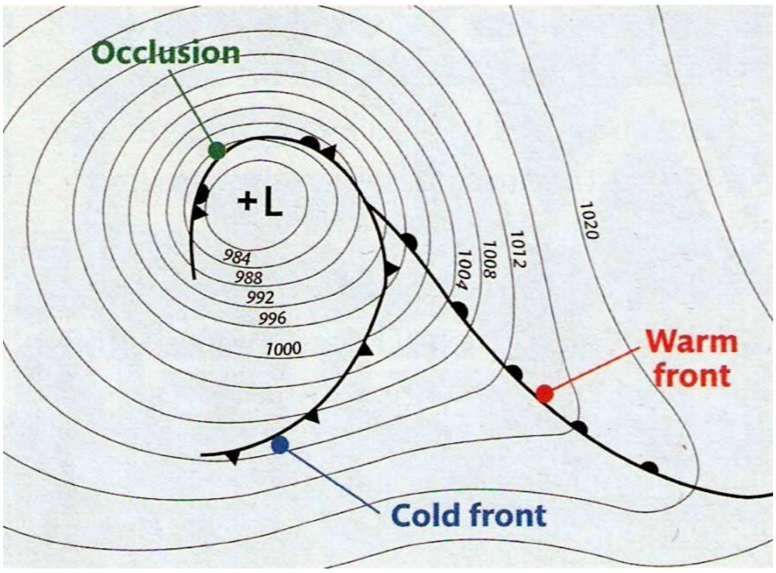


Diagram of a frontal depression

- If low pressure is passing north of you, you can expect south or southwest winds to "veer" westerly (shift clockwise, or to the right as you look at the wind), then north westerly. These passing depressions are the most common source of changing weather in north latitudes.
- The closer the isobars, the stronger the wind. A pressure drop of 5mb within a distance of 200Sm may mean a force 7 wind.
- Highs (anticyclones) bring settled weather. Lows are usually more active, especially if you are going to be involved with the "fronts" which spread out – generally in a southerly direction – from the centre.

- A “warm front” is the first to arrive. It may initially back the wind (shift to the left i.e. anticlockwise) as far round as south – east before bringing a steady veer with increasing cloud cover and rain. The barometer which has been falling now steadies.

A halo around the sun is caused by very high clouds and indicates a warm front coming up behind. The moon does the same thing if it’s full.

- You arte now in the “warm sector”, with tropical maritime air that’s comparatively warm and muggy, often with rain in a south-westerly air stream.
- A few hours later as the “glass” rises, the cold front can bring a sharp veer – perhaps to the northwest, plus heavy showers, maybe with hail and thunder, and big, white clouds called cumulonimbus pile up with anvil-headed tops. Cooler, fresher air rushes down from the north.

Retreating cold front with cumulonimbus cloud

- After the cold has passed, there is a reasonable chance for some decent weather.
- Finally, when a warm front catches up with the cold one, they meld together to form an “occlusion”. These generally veer the wind as well, but the weather pattern is difficult to predict.

Weather forecasts should be continuously checked every hour on passage and every four hours in port, by logging the aneroid barometer reading or by means of an electronic barometer able to record trends. The "glass" can confirm or give the lie to a broadcast bulletin, as prophesy turns into reality with the spinning of the earth. The fact that the instrument is e.g. going down earlier than expected, suggests that the incoming system is moving more rapidly than predicted.

In general terms, a forecast of wet and windy weather will often involve a warm front followed by the full depression cycle. The first sign of the front is typically a run of high, mare's tail cirrus clouds, followed by ever-decreasing cloud height, backing and increasing wind, then rain.

Mare's tail cirrus clouds

All the while the "glass" will be falling. The important question for the sailor is however what the rate of the decreasing atmospheric pressure means? The following rules of thumb for interpreting the rate of decrease of the barometer ridings are quite helpful:

- If it is dropping at 1mb per hour, it will probably blow force 6.
- If it starts plunging at 2mb per hour for more than a couple of hours, he is likely in for a moderate gale.
- If it is dropping at three or more he would really want to be somewhere else.

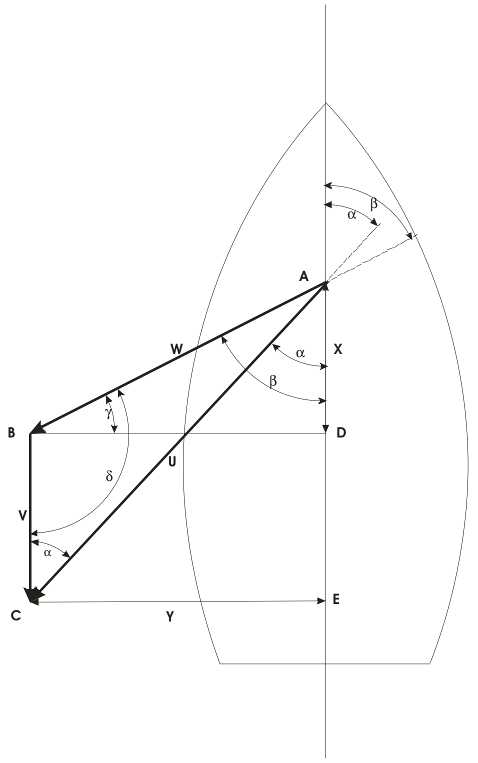
The same rules of thumb apply to a rising barometer, especially after a cold front. Sometimes the wind drops quite suddenly and stipulates it is all over, but a sharp rise after low means a stronger blow. If the "glass" is going up like a "lift", stand by as the breeze will be back with a vengeance before it is finished.

APPENDIX H

(Sailing upwind)

Wind speed and its direction are measured on board of a vessel by a masthead transducer consisting of an Anemometer measuring the wind speed in Knots and a wind vane exhibiting the angle between the longitudinal axis of the vessel and the direction the wind is acting in degrees.

If the vessel has cam to complete stand still, the figure exhibited below indicates a wind acting with a speed magnitude of **W** knots at an angle **β**. In this particular case the data provided by the apparatus are those of the so called **"True wind"**.



Apparent wind speed U = f (Vessels speed V)

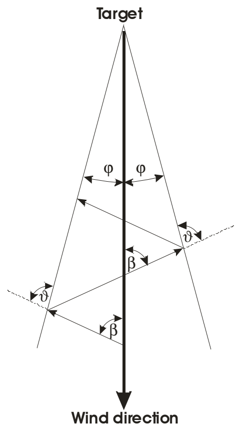
However the data provided by the masthead transducer with the vessel moving forward at a speed **V**, stipulate a wind acting with a speed magnitude of **U** knots which is obviously greater than **W**, and at an angle **α**, which is apparently smaller than **β**. In spite of the fact magnitude and angle of the True wind remained constant, the forward movement of the vessels creates an **"Apparent wind"** acting with a greater force than the true wind and a smaller angle of attack.
It is therefore obvious that a vessel traveling at increasing speed relative to the prevailing wind will encounter the wind driving the sail at a decreasing angle and increasing velocity. Eventually, the increased drag and diminished degree of efficiency of a sail at extremely low angles will cause a loss of accelerating force. This constitutes the main limitation to the speed of wind-driven vessels and vehicles.

How closely a boat can sail into the apparent wind depends on the boat's design, sail shape and trim, the sea state, and the wind speed. Typical angles to the wind are:

- about 35° for modern racing yachts which have been optimized for upwind performance (like Americas cup yachts)
- about 42 to 45° for modern cruiser-racer yachts (fast cruising yachts)
- about 50 to 60° for cruisers with an emphasis on interior space, ease of handling and often low draught rather than sailing performance, and for boats carrying two or more masts (since the forward sails adversely affect the aft sails when sailing upwind)
- close to 90° for square riggers and similar vessels due to the sail shape which is very ineffective when sailing upwind

A basic rule of sailing is that it is not possible to sail directly into the wind, simply because the angle of attack of the wind on the sail would be zero. Generally speaking, a modern boat can sail 45° off the wind. When a boat is sailing this close to the wind, it is **close-hauled** or **beating**. Because a boat cannot sail directly into the wind one can only get to an upwind destination by sailing close-hauled with the wind coming from one side, then tacking and sailing with the wind coming from the other side. By this method of zigzagging into the wind it is possible to reach any destination directly upwind. However when beating the master of the vessel should be aware that there is a word describing beating as a sailing for twice the distance at half the speed and three times the discomfort.

Furthermore in order to avoid any adverse implications created by sudden wind shifts, when beating for a long period of time to a destination directly upwind, the vessel should - until is close to the target - remain inside a cone of **φ = 5°** of each side of the middle axis defined by the wind direction through the destination. Once the vessel is close to the target the cone angle can be increased to **φ = 10°.**



Using a series of close-hauled legs to beat a course upwind.

The important question to the navigator is when he is about to leave the 5° cone area and therefore when he should tack from port to starboard and vice versa in order to make sure he is always sailing inside the cone area. The answer to the question is therefore the knowledge of the angle ϑ, i.e. the angle enclosed between the course of the vessel and the bearing of the target, which is nothing else than the angle of the true wind corrected by φ.

$$\vartheta = \beta \pm \varphi$$

Based on the values provided by the vessels log for its speed through the water **(V)** in knots, the magnitude of the apparent wind **(U)** in knots**,** and the value of the angle of attack **(α)** in degrees as exhibited by the masthead transducer, the magnitude of the true wind **(W)** can be calculated by the cosines law equation exhibited in §5320 as follows:

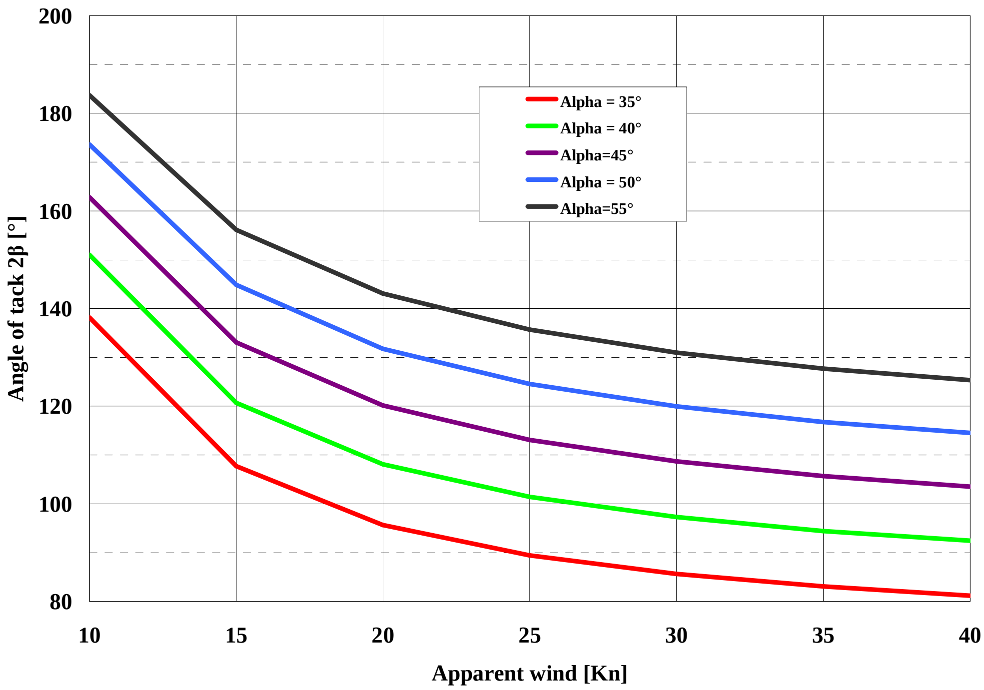
$$W[kn] = \sqrt{U^2 + V^2 - 2*V*U*\cos a}$$

Using the cosines definitions for the angle of attack [cosα = (X+V)/U] and for the angle of the true wind (cosβ = X/W) and substituting W by the formula exhibited above, the angle of the true wing can be calculated as follows:

$$\beta = \arccos \frac{U*\cos\alpha - V}{\sqrt{U^2 + V^2 - 2*V*U*\cos\alpha}}$$

Using the formulas exhibited above one can find out that if the master of a vessel sailing close hauled at an apparent wind of U = 25 Kn with an angle of attack of α = 40° and a speed over ground of V = 6 Kn wish to remain inside a 5° cone, should tack if the bearing of the target relative to the vessels heading does not exit 62°. With respect to the upwind sailing performance of the vessel one can expect the vessel to be able to tag under these conditions through an angle of (62 - 5) * 2 = 114°.

The diagram below exhibits the influence of the best achievable angle of attack to the angle of tack of a vessel beating with a constant SOG=6 Kn at various apparent wind magnitudes.



Upwind performance of a vessel beating at SOG=6 [Kn]

APPENDIX I

(Comparison of radio navigation System accuracies)

System	95% accuracy Lateral/vertical	Comments
LORAN-C specification	460m / 460m	Specified absolute accuracy of the LORAN-C system
LORAN-C Measured repeatability.	50m / 50m	The U.S. Coast Guard reports "return to position" accuracies of 50 meters in time difference mode.
eLORAN repeatability	??	Modern LORAN-C receivers, which use all the available signals simultaneously and H-field antennas.
Distance Measuring Equipment **(DME)** specification	185m (Linear)	DME is a radio navigation aid that can calculate the linear distance from an aircraft to ground equipment.
GPS specification with Selective Availability **(SA)** turned on.	100m / 150m	Selective Availability option was applied by the U.S. Government until 01.05.2000.
GPS measured.	205m / 4,7m	The actual measured accuracy of the system excluding receiver errors, with Selective availability turned off, based on the findings of the FAA's National Satellite Test Bed (NSTB).
Differential GPS **(DGPS)**	10m / 10m	This is the worst-case DGPS accuracy. According to the 2001 Federal Radio navigation Systems (FRS) report published jointly by the U.S. DOT and U.S. DOD accuracy degrades with distance from the facility.
Wide Area Augmentation System **(WAAS)** specification	7,6m / 7,6m	This is the worst case accuracy the WAAS must provide if it shall be used for precision approaches.
WAAS measured.	0,9m / 1,3m	The actual measured accuracy of the system excluding receiver errors, based on the NSTB findings
Local Area augmentation System **(LAAS)** programme.	<1m	The goal of the programme is to provide **Category III (ILS)** capability, to allow aircraft to land with zero visibility using autoland systems.

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Apart from the publications exhibited above information from additional sources like yacht master courses, web and oral information have been used as descriptive material for the compilation of this compendium. However, it should clearly understood, that where third parties information complied with the spirit of this compendium, sentences, paragraphs, figures or pictures of said information have been adopted and where applicable used unchanged in the compendium.