central meridian, central to that zone, to which all grid lines are parallel or perpendicular. The origin of each of the grid zones is the intersection of its central meridian with the equator. Each grid origin is assigned false coordinates which are 500,000 metres east and 0 metres north for the northern hemisphere, and 500,000 metres east and 10,000,000 metres north for the southern hemisphere. This effectively creates false origins 500 km west of the true origins on the equator, for the northern hemisphere, and 500 km west and 10,000 km south of the true origins for the southern hemisphere. UTM Grid coordinates are given in terms of metres east and metres north of the false origin in the hemisphere of the UTM grid zone in which the point falls. Some UTM grid zones are extended at the expense of others. These are shown in Table 1. Depending on the scale of the chart, the distance between the grid lines shown is 10,000, 1,000 or 100 metres. The distance between the grid lines shown is termed the 'grid interval'.

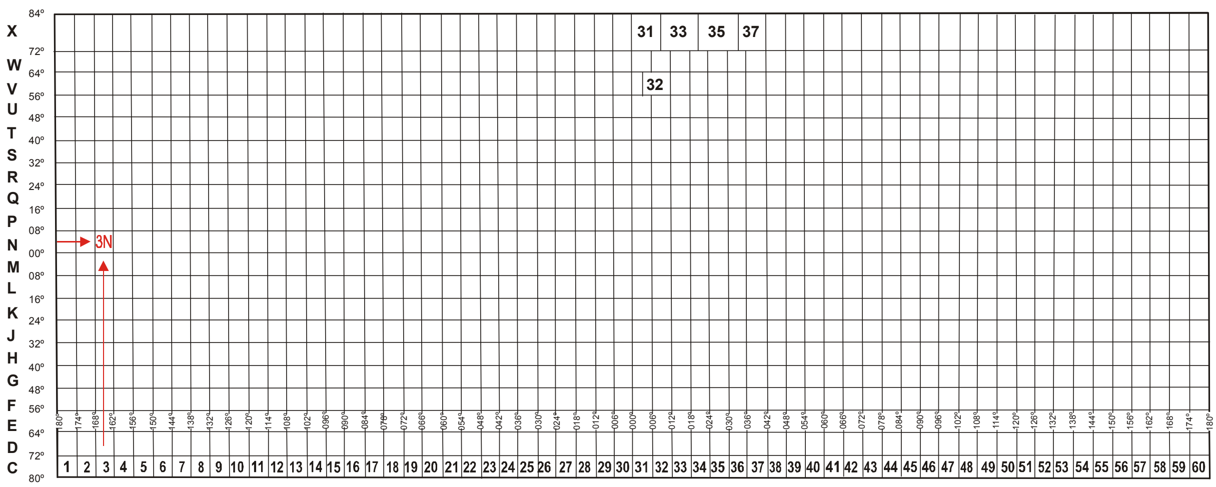
9-2 Table 1 Extended UTM Grid Zones

Latitude Band	Zone	Width
55° N to 64° N	31	3° (0° to 3° E)
	32	9° (3° E to 12° E)
72° N to 84° N	31	9° (0° to 9° E)
	32	Eliminated
	33	12° (9° E to 21° E)
	34	Eliminated
	35	12° (21° E to 33° E)
	36	Eliminated
	37	9° (33° E to 42° E)

22. The UTM grid is further divided into twenty bands of latitude. Each band covers eight degrees of latitude, (except for the most northerly band which covers the twelve degrees between 72° N and 84° N). Each band of latitude is given a designation letter from C to X (omitting letters I and O) starting at 80° S and continuing to 84° N.

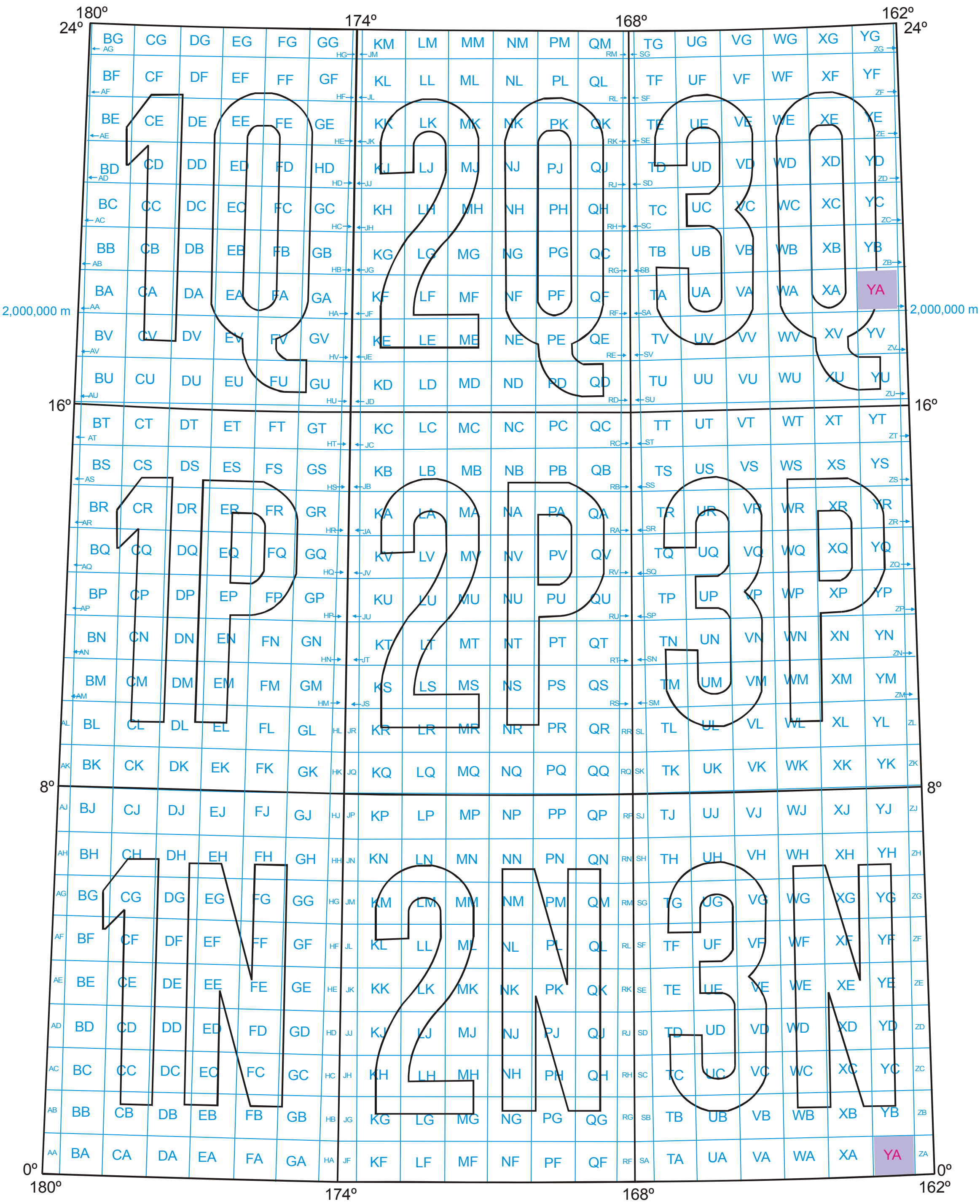
23. Grid Zone Designation Areas are formed by the intersection of the UTM Grid Zones and the latitude bands. Each Grid Zone Designation Area is identified by a unique Grid Zone Designation (GZD). The GZD consists of the number of the UTM grid zone followed by the designation letter of the latitude band. Grid Zone Designation Areas are illustrated in Fig. 10.

9-2 Fig 10 The UTM Grid



24. Each Grid Zone is sub-divided into columns and rows to form 100,000 metre (100 km) squares (Fig 11). Each column and row is given an identifying letter. Thus, each 100,000 metre square is identified by two letters corresponding to its column and row respectively. This pair of letters is termed the 100,000 metre square identification. Because the UTM Grid covers much of the Earth's surface, 100,000 metre square identifications will be repeated. To identify individual 100,000 metre squares, the square identification is preceded by the grid zone designation. In Fig 11, it can be seen that there are two 100,000 metre squares designated YA but they are differentiated by the prefix of their UTM Grid Zone Designation Area, (in this case 3Q and 3N). The 100,000 metre squares are fitted into each 6° zone so that they are uniformly spaced about the central meridian of the zone and along the equator. As a result, the 'grid squares' along the borders of the 6° zones do not form squares.

9-2 Fig 11 Identification of 100 km Squares on the UTM Grid



25. Starting at the 180º meridian and moving eastwards for 18º along the equator, the 100,000 metre columns (including those along 6º zone borders) are lettered alphabetically from A to Z (with I and O omitted). This is repeated at 18º intervals.

26. In odd numbered UTM Grid Zones, the rows of 100,000 metre squares are lettered northwards alphabetically from A to V (with I and O omitted), the partial alphabet being repeated every 20 rows. In even numbered UTM Grid Zones, starting at the equator, the rows are lettered F to V (omitting I and O) followed by A to V (omitting I and O). This is done to increase the distance between 100,000 metre squares with the same square identification. Below the equator, the 100,000 metre rows are lettered northwards in such a way that they fit into the sequence of letters above in the same zone.

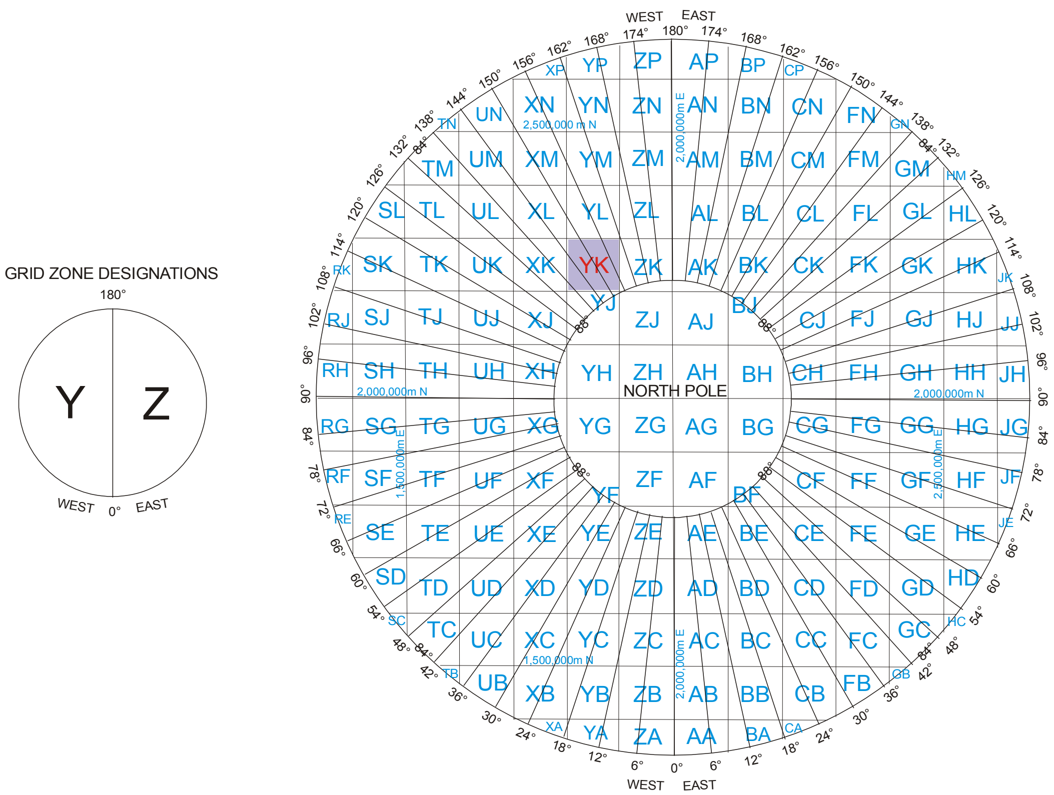
THE UNIVERSAL POLAR STEREOGRAPHIC GRID

Description of the Grid

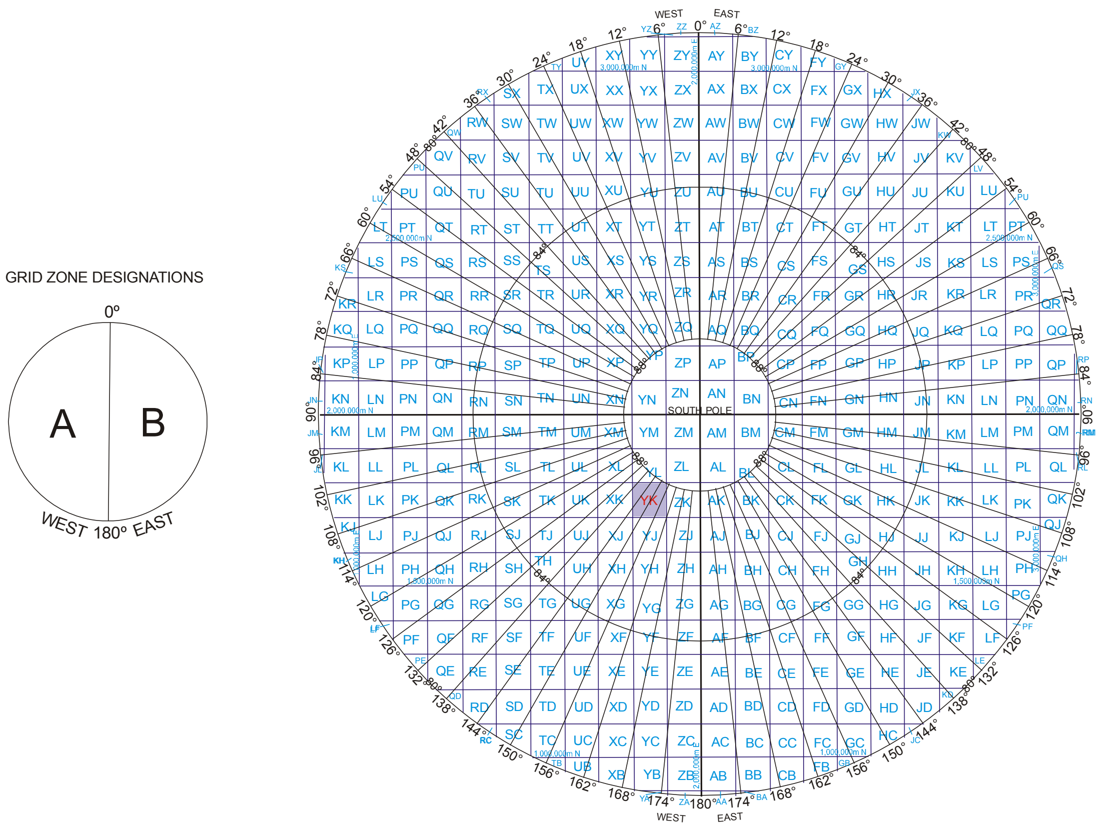
27. The Universal Polar Stereographic Grid consists of two grids - one covering the North Polar area, (north of 84º N), and the other, the South Polar area (south of 80º S). These grids are based on a polar stereographic projection with the origin of each at the respective pole. The Northern and Southern UPS grids extend to 83º 30' N and 79º 30' S respectively to provide a 30' overlap with the UTM grid. Easting grid lines are parallel to the Greenwich Meridian (0º) and the 180º meridian. Northing grid lines are parallel to the 90º W and 90º E meridians. The grid origins are assigned false coordinates of 2,000,000 metres east and 2,000,000 metres north. When used in conjunction with the UTM grid the UPS Grids provide world-wide coverage.

28. The North polar area is divided into two parts by the Greenwich and 180º meridians (Fig 12). The half containing the West longitudes is given the grid zone designation Y whilst that containing the East longitude is given the grid designation Z. Similarly, the South polar area (Fig 13) is divided into two halves. The half containing the West longitudes is lettered A, whilst the other half, containing the East longitudes, is lettered B. No numbers are used in conjunction with these letters.

9-2 Fig 12 The UPS Grid - North Polar Area



9-2 Fig 13 The UPS Grid - South Polar Area



29. Both polar regions are divided into 100,000 metre squares in a similar manner to the UTM system. Columns are defined to be parallel to the 180º /0º meridian and rows parallel to the 90º W/90º E meridian. In the eastern hemisphere, columns are lettered consecutively eastwards, starting at the 180º/0º meridian with A and omitting the letters D, E, I, M, N and O. In the western hemisphere, the columns start at the 180º/0º meridian with Z and the lettering proceeds backwards through the alphabet omitting W, V, O, N and M. The omission of the letters shown ensures that there is no duplication with UTM references within 18º in any direction. In the North polar region, rows start with A at 84º N 0º E, the letters increasing northwards to the Pole, then southwards finishing with P at 84º N 180º E and omitting I and O. In the South polar region, rows start with A at 80º S 180º E, the letters increasing southwards to the Pole, then northwards finishing with Z at 80º S 0º E and omitting I and O.

THE MILITARY GRID REFERENCE SYSTEM

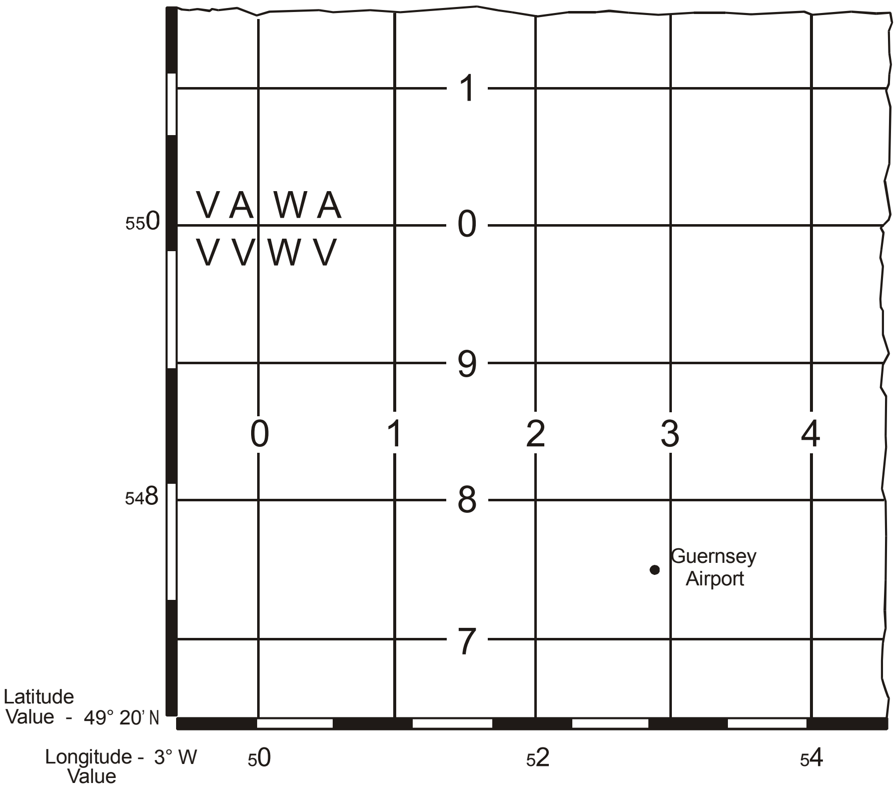
Description of the System

30. The Military Grid Reference System (MGRS) is a grid reference system designed to be used with the UTM and UPS grids. It is a method of defining any point by means of a Grid Reference. A full grid reference is reported in the same way as that for the British National Grid (see para 16), and consists of the Grid Zone Designation (see para 23 for the UTM Grid and para 28 for the UPS Grid), followed by two letters representing the square identifications, followed by an even number of digits that identify a position within the grid square.

31. Most military maps and charts that carry the UTM Grid have a grid reference box in the margin that explains how to report a grid reference. The grid reference box will indicate the Grid Zone Designation(s) applicable to the map or chart. On larger scale products, the grid reference box will also show the grid square identifications that fall on the map or chart.

32. The MGRS Grid reference of the point marked Guernsey Airport in Fig 14 is obtained in the following manner:

9-2 Fig 14 Example Grid Reference



Grid Zone Designation 30U*

*(This can be found from the grid reference box on the chart, ONC E1 in this example)

100 km square identifier WV
Easting 2 followed by 9 (estimated tenths)
Northing 7 followed by 5 (estimated tenths)

Full grid reference
Guernsey Airport 30UWV2975

This four figure reference defines the point to a precision of 1,000 metres.

WORLD GEOGRAPHIC REFERENCE SYSTEM (GEOREF)

Introduction

33. The use of latitude and longitude as a method for reporting position suffers from the disadvantages stated in para 12. These disadvantages can be overcome by the use of a reporting system based on a lettered rectangular grid. However, rectangular grids which ignore the curvature of the earth, while satisfactory over a limited area, become excessively distorted with any great extension of the area of use. To avoid this distortion, any reference system which is to have universal coverage, must be based on the graticule of meridians and parallels.

34. The World Geographic Reference System (GEOREF) was introduced with the object of providing a simple, speedy, unambiguous method of defining position which is capable of universal application. It incorporates the best of both systems by utilizing the orthodox graticule of meridians and parallels and by

expressing the position of any point, in relation to it, by a system of alphanumeric references. In this way, the disadvantages of latitude and longitude (stated in para 12 sub-paras a and b) are overcome.

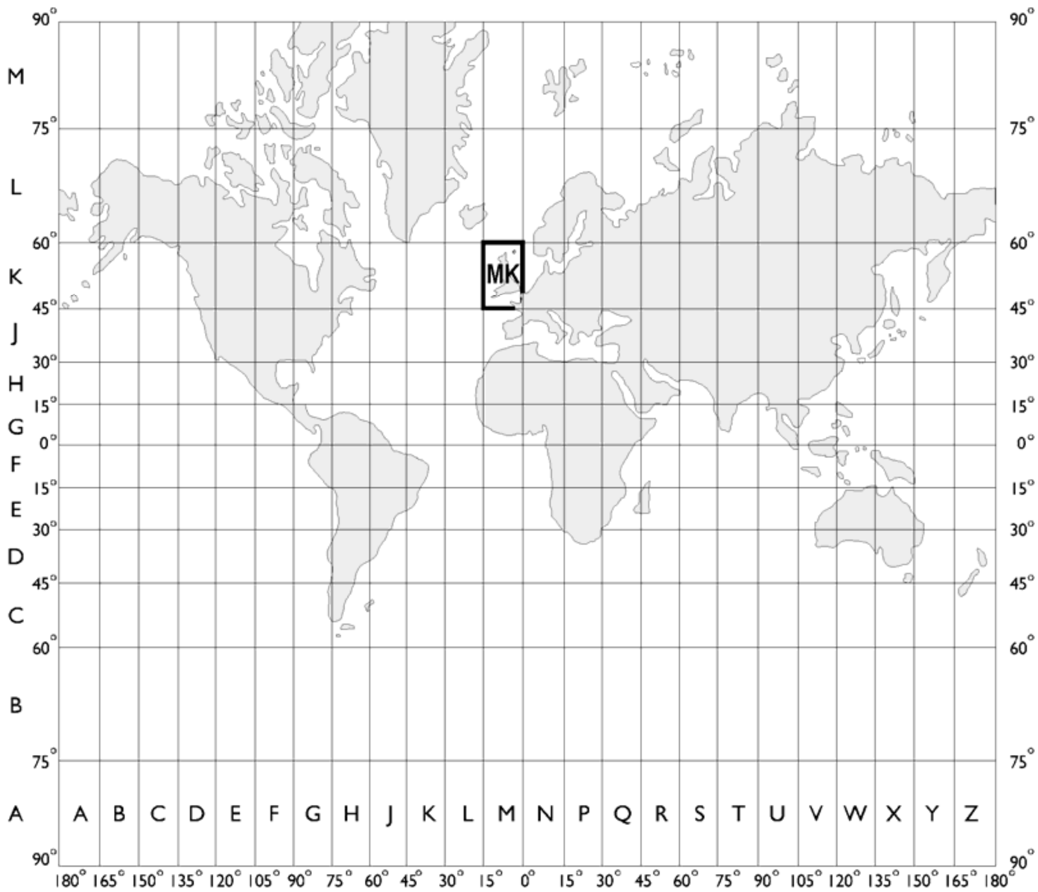
35. It is emphasized that the GEOREF system replaces neither the latitude and longitude nor the rectangular grid methods of reporting positions. However, it provides a convenient means of reporting position within the framework of the latitude and longitude system.

Description of the System

36. The GEOREF system divides the surface of the Earth into quadrangles, the sides of which are specific arc lengths of longitude and latitude. Each quadrangle is then identified by a simple, systematic, lettered code.

37. The first division of the Earth's surface is into 24 longitudinal zones, each 15º wide, which are lettered A to Z inclusive (omitting I and O), commencing eastwards from the 180º meridian. A corresponding division is made of the Earth's surface into 12 latitudinal bands, each 15º wide, which are lettered A to M inclusive (omitting I), commencing northwards from the South Pole. The Earth is therefore divided into 288 quadrangles, of 15º sides, each of which is identified by a unique combination of two letters. The first letter is always that of the longitude zone or easting, and the second that of the latitude band or northing. In this respect, the system differs from that of latitude and longitude in which the latitude is always given first. For example, in Fig 15, it can be seen that the majority of the UK is in the 15º quadrangle MK.

9-2 Fig 15 GEOREF System of 15º Identification Letters

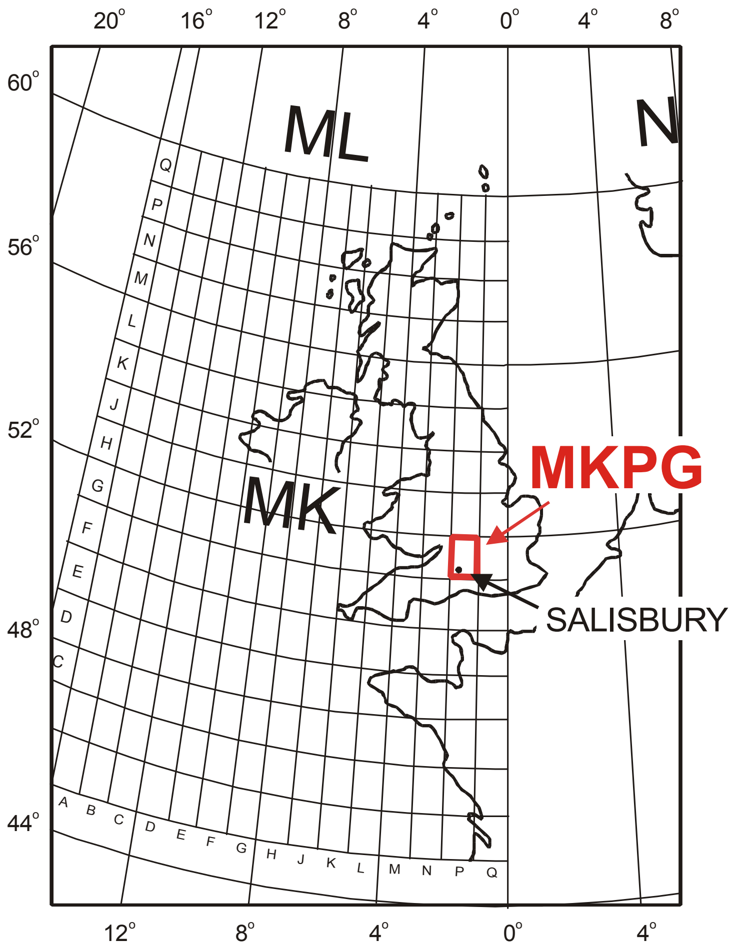


38. Each 15º quadrangle is now sub-divided into 15 one-degree longitudinal zones and latitudinal bands, lettered A to Q inclusive (omitting I and O), commencing eastwards and northwards

respectively from the South-West corner of the 15° quadrangle. Thus, the 15° quadrangles are sub-divided into 225 one-degree quadrangles, each being identified by means of four letters. The first two letters identify the 15° quadrangle, the third letter the one-degree zone of longitude, and the fourth letter the one-degree band of latitude.

39. Salisbury, in the County of Wiltshire, therefore lies in the one-degree quadrangle MK PG (see Fig 16).

9-2 Fig 16 One-degree Quadrangles



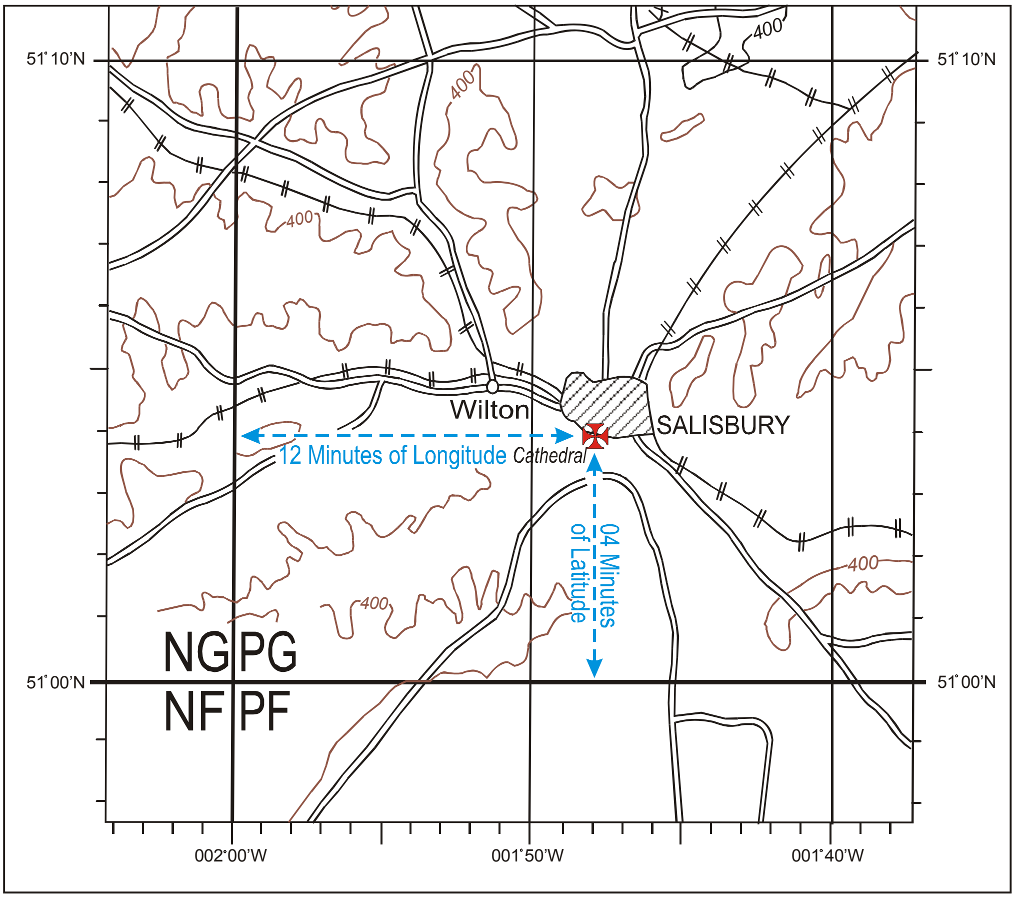
40. Each one degree quadrangle is divided into sixty minutes of longitude, numbered eastwards from its western meridian, and sixty minutes of latitude, numbered northwards from its southern parallel. This method of numbering is used no matter where the one degree quadrangle is located, and does not vary even though the location may be west of the Prime Meridian or south of the equator.

41. A unique reference defining the position of a point to a precision of one minute in latitude and longitude (a precision of 2 km or less) can now be given by quoting four letters and four numerals. The four letters identify the one degree quadrangle. The first two numerals are the number of minutes of longitude by which the point lies eastward of the western meridian of the one degree quadrangle. The second two numerals are the number of minutes of latitude by which the point lies northward of the southern parallel of the one degree quadrangle. If the number of minutes for either of the longitude or latitude values is less than ten, the first numeral of the pair will be zero and must be written. Thus the reference of Salisbury Cathedral (51° 04' N 001° 48' W) is MKPG 1204 (see Fig 17).

42. Occasions may arise (very infrequently) when it is necessary to define a position to an accuracy greater than one minute. The GEOREF system can be expanded to allow for this. A reference to one tenth of a minute of longitude and latitude is obtained by a further sub-division of the one-minute quadrangle into tenths of a minute of longitude eastwards and into tenths of a minute of latitude

northwards from the bottom left-hand corner of the minute quadrangle. The accuracy is now approximately 608 ft, and the reference is given by quoting six numerals instead of four. A further refinement to an accuracy of approximately 61 ft is obtained when the eastings and northings are given additional figures. In this case, the first four numerals represent the eastings in minutes and hundredths of a minute of longitude and the remaining four numerals represent the northings to a similar accuracy. Thus the GEOREF of Salisbury Cathedral, to an accuracy of one-tenth of a minute, is MKPG 122039 and to a hundredth of a minute, MKPG 12250386 (see Fig 17).

9-2 Fig 17 Part of the One-degree Quadrangle containing Salisbury Cathedral in detail



43. On local operations, where the risk of ambiguity with a neighbouring 15º quadrangle is unlikely, the first two letters of the reference may be dropped. The reference given in para 41 would then become PG 1204.

44. When a position lies on a dividing meridian of two longitudinal zones, or a dividing parallel of two bands of latitude, the reference letters quoted are for the most easterly zone or the most northerly band; e.g. the GEOREF of 50º N 00º W is NKAF 0000 (see Fig 16).

Use of GEOREF

45. The GEOREF system is used specifically in:

a. The control and direction of forces engaged in the air defence of the United Kingdom and the countries of the North Atlantic Treaty Organization.

b. The coastal defence of the United Kingdom.

46. Although the system has a restricted use, it is available for universal application should the occasion arise. Whenever security demands, it is a simple operation to change the code letters periodically.

Conversion of Latitude and Longitude to GEOREF Co-ordinates

47. Using the description of the GEOREF system (para 36) and Fig 15, a method of deriving a GEOREF coordinate from a latitude and longitude position can be determined. It must be remembered, when following the example below, that in the latitude and longitude system, latitude is always written before longitude, but, in the GEOREF system, the longitude value is written before the latitude value.

Example: To convert 55º 05' N 010º 29' W to GEOREF

a. Apply the conventional signs for N(+), S(–), E(+) and W(–) to the latitude and longitude position. Thus, 55º 05' N 010º 29' W becomes +55º 05' –10º 29' (The preceding zero can dropped from the longitude degree value).

b. Add 90º to the latitude and 180º to the longitude.

90º 00'	180º 00'
+55º 05'	–10º 29'
145º 05'	169º 31'

c. Divide both of the whole degree portions (145 and 169) by 15:

$$15\,\overline{)145} = 9 \qquad 15\,\overline{)169} = 11$$

(This gives respective quotients of 9 and 11)

135	165
10	4

(This gives respective remainders of 10 and 4)

d. Add 1 to the quotients: 9 + 1 = 10 and 11 + 1 = 12.

e. Write down the letters corresponding to these numbers, omitting I and O in the count.

A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U	V	W	X	Y	Z
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

The longitude value (12) gives M and the latitude value (10) gives K.

f. Combine the letters to give MK; this is the 15º quadrangle identifier.

g. Add 1 to each remainder: 10 + 1 = 11 and 4 + 1 = 5.

h. Write down the letters corresponding to these numbers, omitting I and O in the count.

The longitude value (5) gives E and the latitude value (11) gives L.

i. Combine the letters to give EL; this is the 1º quadrangle identifier.

j. The numerical portion of the GEOREF is taken from the minutes part of the latitude and longitude values **after** the sum in sub-para b. The longitude minutes are 31 and the latitude minutes are 05.

k. Thus 55º 05' N 010º 29' W corresponds to MKEL 3105 in GEOREF.

Advantages and Disadvantages of the GEOREF System

48. **Advantages.**

a. GEOREF provides an easy and quick method of position reference.

b. There is no risk of ambiguity.

c. It is eminently suitable for use over R/T or telephone.

d. It is capable of universal application.

e. For purposes of security, it is comparatively simple to change the code letters periodically.

f. To provide a reference to a precision of l minute, the group is smaller than the corresponding reference by latitude and longitude.

49. **Disadvantages**.

a. Like the latitude and longitude system, it compares unfavourably with a rectangular grid, since a different scale has to be used for the measurement of the number of minutes of longitude and latitude.

b. The system can be confusing because, contrary to latitude and longitude procedures, the minutes of longitude are given before the minutes of latitude. Similarly, the method of reporting a GEOREF in the southern and western hemispheres is the same as for the northern and eastern hemispheres.

LOCAL DATUMS

Introduction

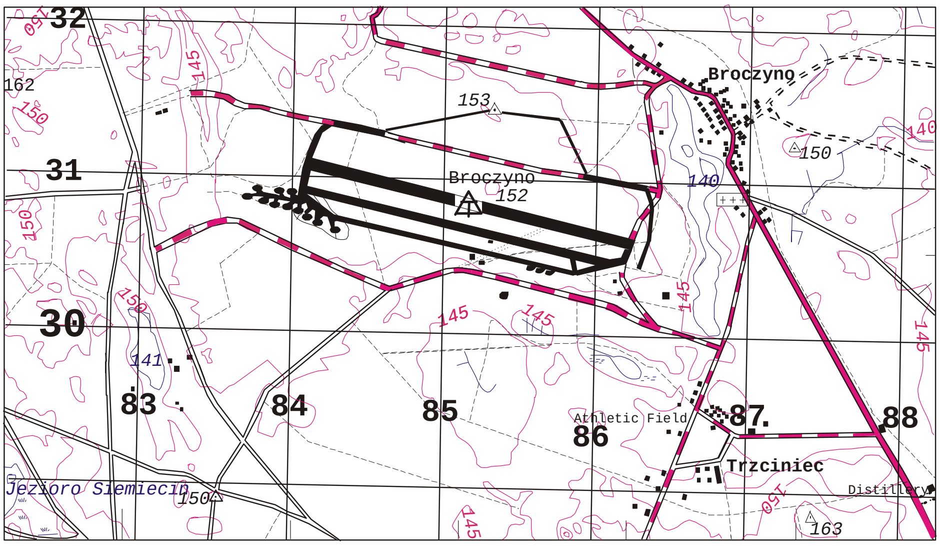
50. A datum can be considered as a set of mathematical constants that define the size and shape of the ellipsoid and how that ellipsoid is fixed to the geoid. It is used in conjunction with the production of a particular map. Despite the introduction of world-wide standards such as WGS 84, many nations still produce maps and charts using local datum references. Provided that all references to position are based upon the same datum, little confusion will ensue. However, co-ordinates for a point on the Earth's surface using one datum will, in most cases, not match the co-ordinates for the same point using another datum.

Error Potential

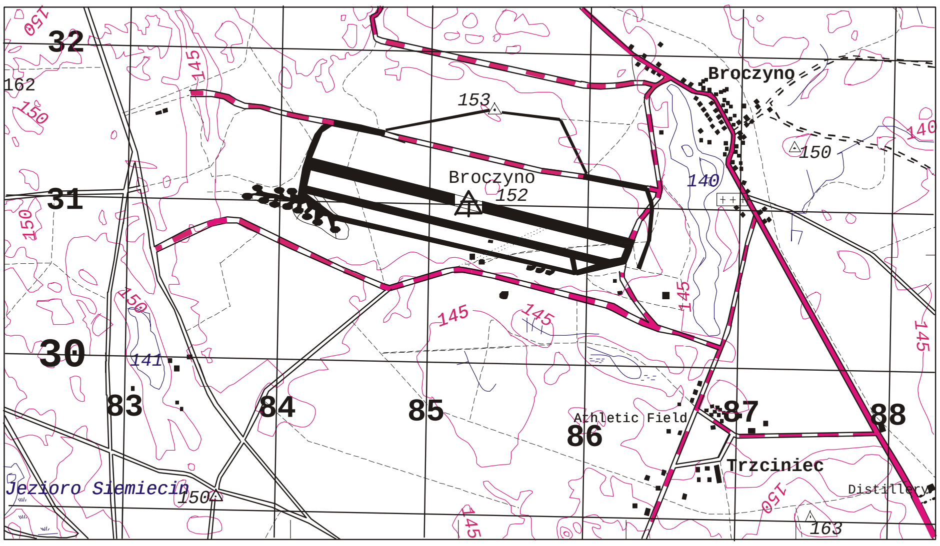
51. Fig 18 shows two maps of the same area but bearing differing grid overlays. Fig 18a is based upon WGS 84 and Fig 18b on the European Datum (ED) 50. The position of the centre of the runway at BROCZYNO can be identified by the co-ordinates 851308 under WGS 84 and as 852310 under ED 50. If this airfield were to be a target, provided that both the target planner and the tasked aircrew were using maps with the same datum, there would be no problem. If not, the position tasked would not be the position attacked.

9-2 Fig 18 Grid Position Comparison

a WGS 84 Grid - Target Position 851308



b ED 50 Grid - Target Position 852310



OTHER METHODS OF EXPRESSING POSITION

Introduction

52. The methods so far discussed have defined position relative to a pair of reference lines. However, there are occasions when simpler methods will suffice.

Pin-points

53. The simplest method of reporting an aircraft's position is to name the point directly beneath the aircraft at that time. This is known as a 'pin-point', and may be a town, airfield, radio beacon etc. However this may be an imprecise method because:

a. Easily recognized features are rarely small.

b. It is difficult for the pilot to determine, and view, the position vertically beneath the aircraft.

c. It relies on the receiving agency's knowledge of the area, and is therefore open to some confusion.

Range and Bearing

54. An alternative method is to express the aircraft's position as a range (distance in nautical miles) and bearing (angular relationship) from an easily identified datum or feature. This method is sometimes referred to as a rho-theta (ρ, θ) system.

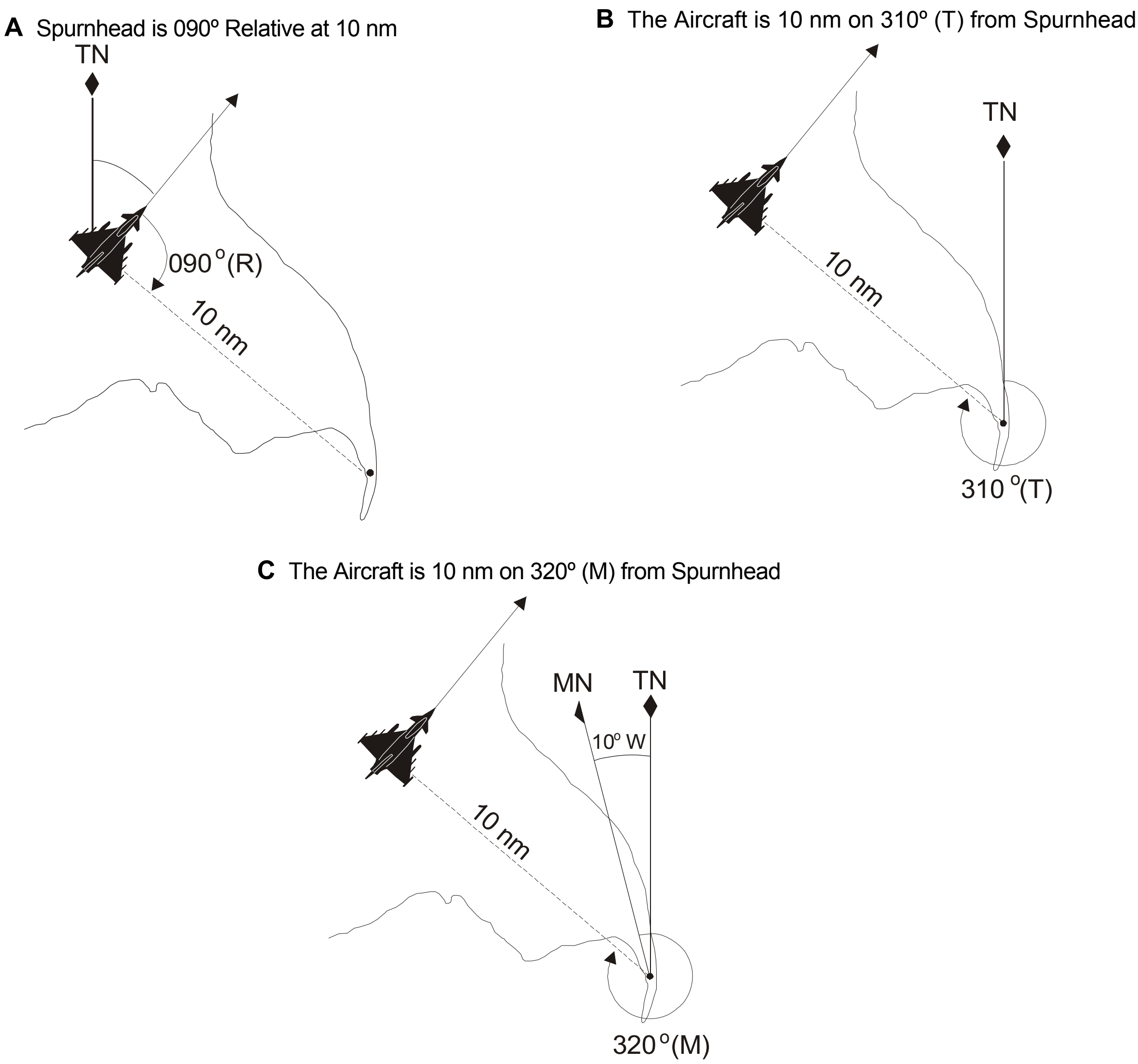
55. Fig 19 illustrates three expressions of bearing for the same aircraft position:

a. Fig 19a shows the relative bearing (measured from the fore-and-aft axis of the aircraft) of the feature from the aircraft. The receiving agency must know the aircraft's heading to interpret this message.

b. Fig 19b shows the true direction of the line joining the feature and the aircraft, measured at the feature. This is known as a 'true' bearing.

c. Fig 19c shows the magnetic direction of the line joining the feature and the aircraft, measured at the feature (known as a 'magnetic' bearing). This method is often used in conjunction with TACAN and VOR/DME beacons, which provide this information directly. When obtained from beacons, magnetic bearings are normally referred to as 'radials', e.g. "I am on the 180 radial from Wallasey VOR", indicates that the aircraft is on a line drawn at 180º (M) from Wallasey VOR.

9-2 Fig 19 Range and Bearing



CHAPTER 3 - MAP PROJECTIONS

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Figures

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Introduction

1. The Earth is an irregularly shaped solid figure whose surface is largely water, out of which the various land masses rise. A map or chart is a representation of this surface at some convenient size on a flat sheet. The term 'map' is generally taken to be a representation of land areas while 'chart' is traditionally reserved for sea area representation. The aviator is not always concerned with this distinction and the air chart covers both. Other terms used are 'plan', to describe a bird's-eye view of a small area, and 'graphic', to describe maps which vividly portray topography.

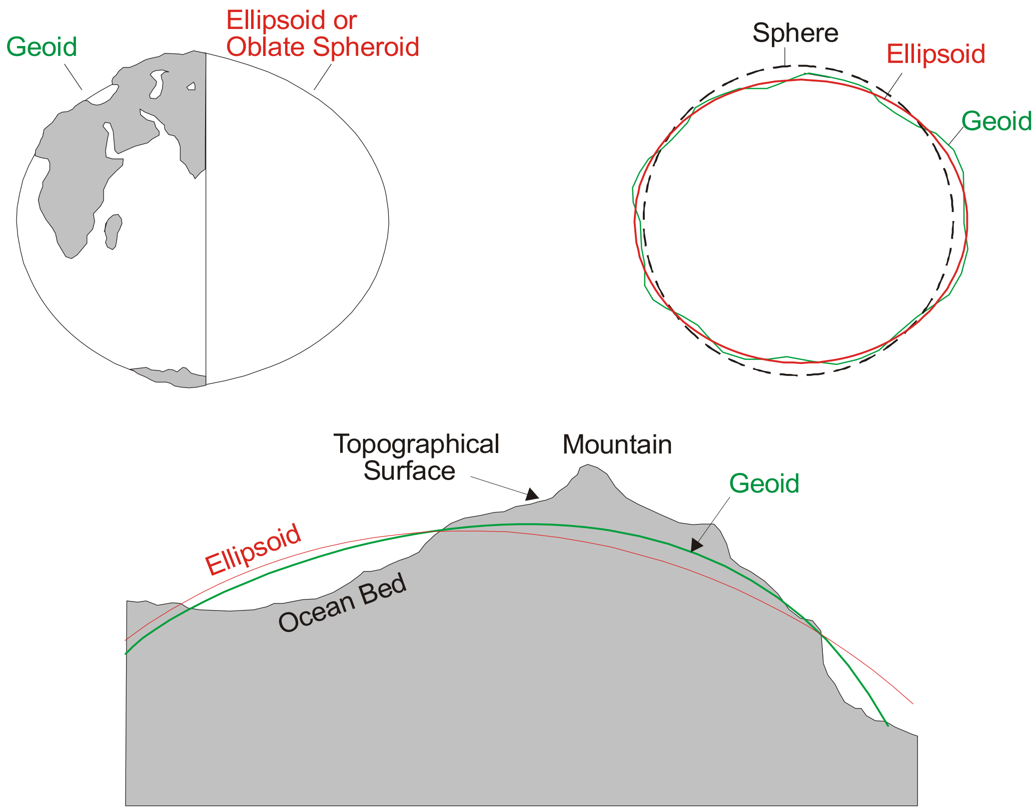
2. A map projection is a systematic laying down of the meridians and parallels on to a flat sheet in such a way that the result displays certain features of the actual surface. There are many ways in which this can be done and clearly a way must be chosen which generates a useful product. However, just as it is meaningless to try to represent a circle by a square, so it is not feasible to represent the Earth's three-dimensional shape on a flat plane in a wholly accurate manner.

3. It would, however, be possible to construct a square which had some features in common with a circle, e.g. the same area, the same perimeter, or the diagonal equal to the diameter. In order to represent all of the circle's features, many different squares would be necessary. Similarly, not all of the Earth's features can be represented accurately on a single map projection. The user must therefore select the correct projection to meet a specific use.

4. For navigation purposes it is important that bearings and distances are correctly represented and easily measured; for convenience the path which is flown should be shown as a straight line and the plotting of radio and other bearings should be straightforward. In order to achieve these characteristics, other properties must be sacrificed; areas may be out of proportion and it may be necessary to restrict the area of coverage of any single map.

5. Before looking at projections and properties closely, the shape of the Earth deserves some more attention. The true topographic surface, with mountains, valleys and oceans, is too irregular for any simple treatment, and it is easier to deal with if approximated by less complicated shapes. There are various possibilities. The water surface (the mean sea surface together with the outline which would be traced if frictionless canals were let into the land masses) is known as the 'geoid'. The geoid is also an irregular surface, but it can be well represented by the smooth surface of an oblate spheroid (or ellipsoid), which is a regular mathematical figure. For many charting purposes, a further simplification can be made by replacing the oblate spheroid by a sphere of the same general size. These are all shown in Fig 1.

9-3 Fig 1 Shape of the Earth



The Vertical Datum

6. The zero surface to which elevations or heights are referred is called the Vertical Datum. Because it is available worldwide, traditionally, surveyors and mapmakers have taken sea level as the definition of zero elevation. The Mean Sea Level (MSL) is determined by continuously measuring the rise and fall of the oceans at 'tide gauge' stations on sea coasts. This averages out the highs and lows of the tides caused by the changing effects of the gravitational forces from the sun and moon, which produce the tides. It is evident, however, that there can be a considerable variation in the average of the local sea level for a particular ocean and that of another. MSL, therefore, becomes more properly defined as the zero elevation for a local or regional area. The heights of mountains or structures on locally produced maps of the area are determined by using the local MSL as the datum. With the advent of satellite navigational systems, which compute heights against a worldwide standard datum, some variation may be observed between heights depicted on the map and those calculated by the instrumentation. If such instrumentation (e.g. Global Positioning System) is being used to provide height information for an instrument approach, it is of paramount importance that the height being presented to the pilot is based upon the same datum as the radar picture being monitored by the approach controller.

Zero Surfaces of Height Systems

7. The differences encountered in height measurements and their representation on maps or equipment displays can be attributed to the differences between the topographic surface of the Earth, the associated flattened spheroid (ellipsoid) and the geoid as described in para 5 and illustrated in Fig 1.

8. **Topographic Surface**. The topographic surface is the actual surface of the Earth tracing the ocean floors to the tops of mountains.

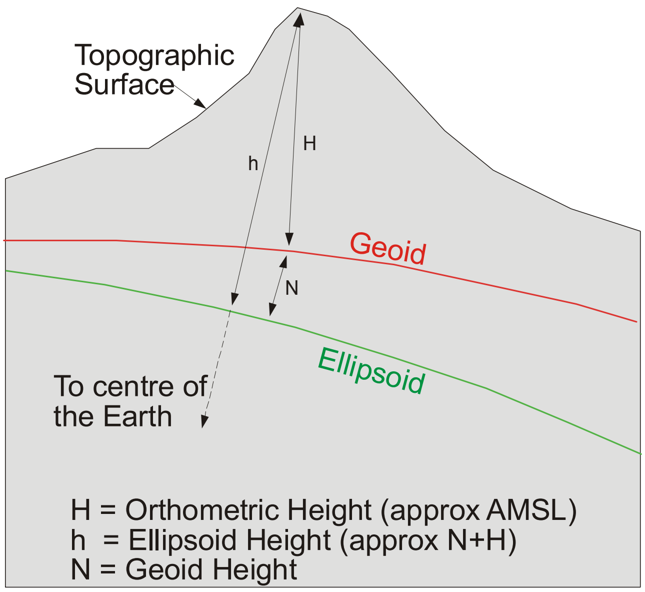
9. **Geoid**. The geoid is the physical model of the Earth and approximates MSL. It is the zero surface as defined by the Earth's gravity. The direction of gravity is perpendicular to the geoid at every point. Variations in the topography and the different densities within the Earth's crust produce slight variations in the gravity field, described by the dips and peaks of the geoid. Since the sea surface conforms to this gravity field, sea level also contains slight hills and valleys similar to, but much smoother than, the topographical surface. At any one point on the ocean, therefore, the sea level may be closer to, or farther from, the centre of the Earth than another such point and this variation may be as much as 5 metres.

10. **Spheroid or Ellipsoid**. The ellipsoid is a smooth representation of the oblate spheroidal shape of the Earth and is used as its geometric model. An ellipsoid is generated by the revolution of an ellipse about one of its principal axes. The ellipsoid which approximates the geoid is an ellipse rotated about its minor axis. In some texts describing the Earth, the term oblate spheroid is abbreviated to spheroid and is synonymous with ellipsoid. The term ellipsoid will be used in this chapter hereafter.

Height Calculation

11. Any zero surface can be used as a datum to express height, even the centre of the Earth. Fig 2 is an enlargement of detail from Fig 1 and shows how each datum discussed may be used to express height.

9-3 Fig 2 Detail from Fig 1 - Representation of Height



12. **Orthometric Height**. Height above MSL is approximately the same as orthometric height (H), the technical name for height above the geoid. There are a few points on land which fall below the geoid, and in such cases H can be negative.

13. **Geoid Height**. Geoid height (N) is the separation between the geoid and the ellipsoid. It can be plus or minus depending upon whether the geoid is further from, or closer to, the centre of the Earth than the ellipsoid. N is positive where the geoid is further from the centre of the Earth than the ellipsoid, zero when they are coincident and negative when the geoid is closer to the Earth's centre.

14. **Ellipsoid Height**. Ellipsoid height (h) is a measure of distance above or below the ellipsoid (plus or minus). h is also called geodetic height. h is approximately equal to N + H.

Height Interpretation by Global Positioning System (GPS)

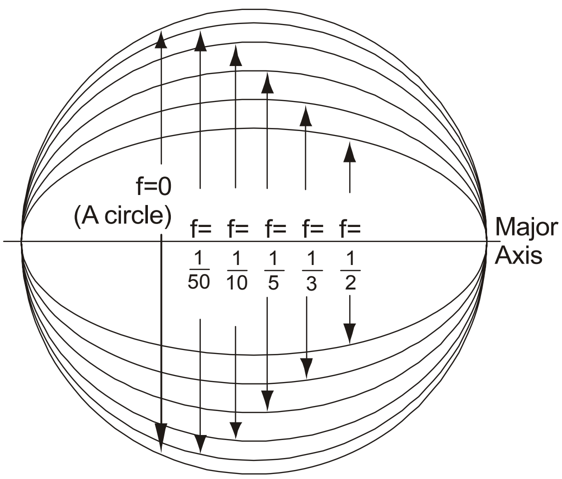
15. GPS receivers normally output elevations based upon the ellipsoid. However, the system has the capability to output height, on demand, converted to MSL and most modern receivers are able to access that option. GPS MSL height is based on the best geoid information available for the area in question and this is being continually improved with technological advances in geodesy and instrumentation.

Map Projections

16. Many maps are drawn on projections of the ellipsoid. As stated in para 10, the ellipsoid is the solid figure generated by rotating an ellipse about its minor axis, Fig 3, and lends itself to a tolerably simple mathematical treatment. The minor axis PP′ is the polar axis and the major axis EE′ is the equatorial axis; an ellipsoid can be defined by stating one radius and the ratio $\frac{a-b}{a}$, known as the flattening (f). A single mean ellipsoid can be used to represent the whole Earth, but because the geoid is irregular an ellipsoid can be found which represents one part of the world with fair precision and yet is unsuitable in another part. Some of the ellipsoids in use are listed in Table 1 below.

9-3 Fig 3 The Ellipsoid

3a – Examples of Flattening



3b – Earth Flattening is Approx 1/300

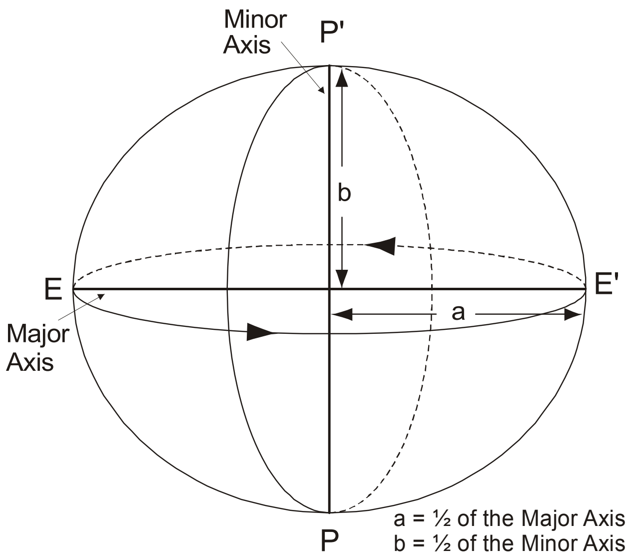


Table 1 Examples of Ellipsoids in Use

Area	Ellipsoid Name	Radius km	Radius nm	Flattening
Russia	Krassovsky	6378.250	3443.98	1/298.3
N America	Clarke 1866	6378.206	3443.96	1/295.0
Europe	International 1909	6378.388	3444.05	1/297.0
Japan	Bessel 1841	6377.397	3443.52	1/299.2
Africa	Clarke 1880	6378.249	3443.98	1/293.5
India	Everest	6377.276	3443.46	1/300.8
World Geodetic System 1972 (WGS72)		6378.135	3443.55	1/298.3
World Geodetic System 1984 (WGS84)		6378.137	3443.56	1/298.3

17. Because of the difference between the ellipsoids, the position discrepancies between maps based on neighbouring ellipsoids can give errors as great as 1500 m. However, it is possible to select the correct datum in advanced navigation systems to alleviate this.

18. The ultimate simplification of the figure of the Earth is the sphere. The geometry is easy, and projections can be reduced very often to ruler and compass constructions. In the chapters which follow, projections of the sphere, which are often used in practice, are described; projections of the ellipsoids follow similar patterns, but are very much more complicated. From a practical point of view no projection allows precise measurement of bearing and distance, and there is little advantage to be gained from complexity. When great precision is required the quantities are best calculated, rather than measured, from the appropriate ellipsoid.

19. **Summary**. The points which this introduction has attempted to make are as follows:

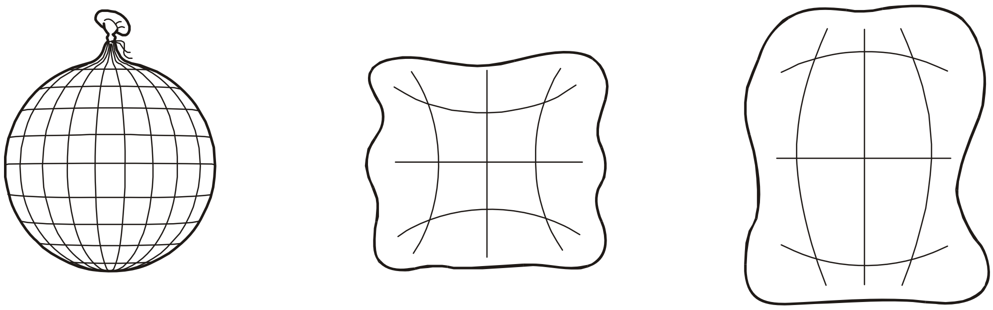
a. The Earth's figure can be described in order of reducing precision as the geoid, an ellipsoid (sometimes called a spheroid) or a sphere. Map projections are drawn using a sphere or an ellipsoid as the figure of the Earth.

b. A map projection is not in general a picture of the Earth. It is a plane drawing on which certain distances, areas, directions, or other features on the Earth required for navigation purposes are reproduced.

Classification of Map Projections

20. A simple insight into the problems of representing the Earth on a flat surface can be gained by imagining a balloon blown up to some manageable size to make a model of the Earth. Having drawn all the shapes and lines on the balloon, it could be deflated and the piece required cut out and stretched to make it flat. Of course it could be stretched more in one direction than another and a great variety of shapes obtained. Each time the flat elastic plane was altered, another map projection would result. Fig 4 illustrates some of the many possibilities.

9-3 Fig 4 Elastic Projections

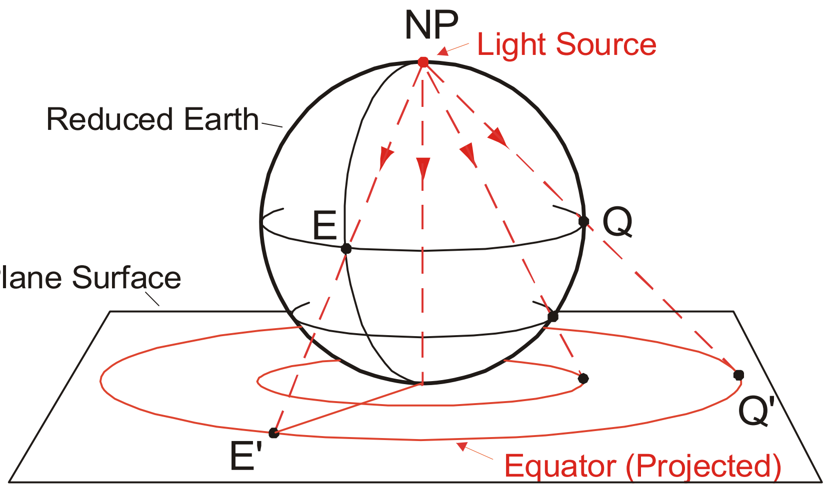


21. Most of the projections obtained in this way would not be very useful. It would be more convenient if the meridians were straight lines for example, and this could be obtained by suitably manoeuvring the material; also by sticking down parts of the rubber the amount of stretch in a given direction could be varied along that direction. But it would be difficult to control the rubber to give any predetermined projection and this model is not used in practice.

22. In actual map projections a relationship between points on the surface of the Earth and the corresponding point on the plane is formulated mathematically. For each of the odd looking diagrams in Fig 3 some such point-to-point relationship exists. The relationship may be a complicated formula involving many variables, or it may be extremely simple.

23. **Perspective Projections**. The simplest relationships are those which can be reproduced by simple geometric construction. They are called perspective projections since they are nothing more than drawings of the shadows which would be cast by the meridians and parallels on a transparent model Earth on to a plane surface, or on to a surface which can be made plane. One example of this is given in Fig 5 where a point source of light at the North Pole of the model Earth (usually called the reduced Earth) projects the meridians and parallels on to a plane tangential at the South Pole. Variety is obtained by moving the light and the plane.

9-3 Fig 5 A Perspective Projection



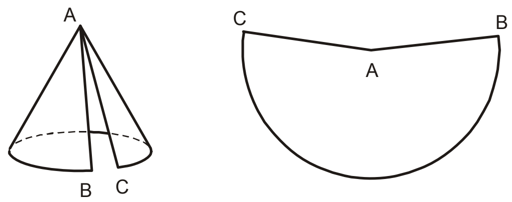
24. **Non-perspective Projections**. When the relationship is such that simple geometric construction is impossible the projection is designated non-perspective. The majority of map projections are non-perspective, but every non-perspective projection can be thought of as perspective projection which has

been adjusted in some way. Hence a study of the simple projections leads without too much difficulty to the more complicated ones. In this section each of the non-perspective projections, which comprise nearly all the most useful ones, will be dealt with under a generic title which really describes its perspective primitive.

Types of Perspective Projections

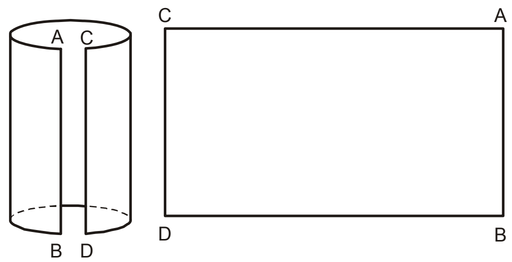
25. The surface on to which the shadows described in para 23 are cast need not be a simple flat surface, and any surface which can be subsequently opened out and laid flat will do. For example a cone (Fig 6) can be placed over the reduced Earth, the projections carried out, and then the cone can be cut and opened (the technical expression is 'developed') to lie flat.

9-3 Fig 6 Development of a Cone



26. A cylinder can also be wrapped around the reduced Earth and developed after projection as shown in Fig 7.

9-3 Fig 7 Development of a Cylinder



27. These three projection surfaces provide the generic titles as follows:

a. Azimuthal projections are perspective projections on to a plane surface, together with certain associated non-perspective projections.

b. Cylindrical projections are perspective projections on to a cylinder, together with the associated non-perspective projections.

c. Conical projections are perspective projections on to a cone, together with the associated non-perspective projections.

28. Variety in each group is obtained by varying the light source position. In fact the classification is somewhat artificial since a cylinder is a cone whose apex angle is 0º, and a plane is a cone whose apex angle is 180º. The cylinder and the plane are therefore limiting cases of the cone.

Representation of Scale

29. The balloon model of the Earth in para 20 was impractical because it would be difficult to control the stretching of the rubber to obtain a particular projection. However, one point was quite clear - stretching was required to lay it absolutely flat. This point is vital. It is not possible to project a sphere on to a plane without at least some elongation taking place.

30. Scale is defined as the ratio of chart length to Earth length; because of the distortion which takes place it is impossible for this ratio to be constant all over any projection and small lengths only can be considered. The rubber can be stretched to make the scale constant along one line for example, or it can expand in all directions from a point; it cannot be arranged to have the same value everywhere.

31. On a great many charts scale changes by different amounts in different directions from a point. It is usual therefore when stating scale to quote where it exists.

32. **Methods of Expressing Scale**. Three methods of expressing scale are in general use:

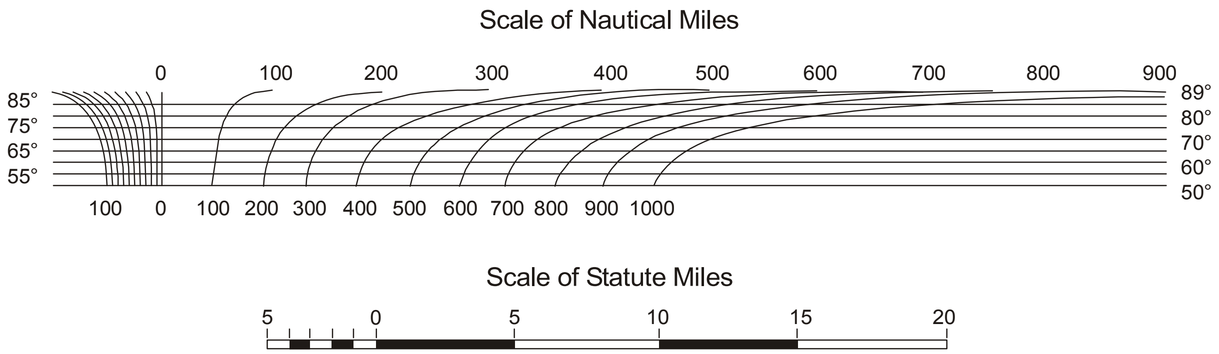
a. The representative fraction, e.g. $\frac{1}{500{,}000}$ or 1 in 500,000, or 1:500,000.

b. The plain statement, e.g. "2 cm to 1 km".

c. The graduated scale, as shown in Fig 8.

In most calculations it is convenient to use the representative fraction; note that 1:500,000 is referred to as a larger scale than 1:1,000,000.

9-3 Fig 8 The Graduated Scale



33. **Scale Factor**. Mention has been made already of the reduced Earth. Since this is a model of the Earth its scale can be expressed as a ratio of Reduced Earth length to Actual Earth length and will be constant. In map projections a reduced Earth of given scale is used as the basis of a given projection; somewhere on each projection a point or line (or lines) will exist with the same scale as the reduced Earth. This is the scale usually printed on maps and charts and scale at other points is determined with the aid of a ratio known as scale factor.

Scale factor is defined as:

$$\text{Scale Factor} = \frac{\text{Chart Scale}}{\text{Reduced Earth Scale}}$$

or

$$\text{Scale Factor} = \frac{\text{Chart Length}}{\text{Reduced Earth Length}}$$

the length being those of a given distance element on Earth.

34. **Scale Deviation**. The stated scale of a chart is usually the reduced Earth scale, hence at a point where stated scale is correct (ie where Chart scale equals Reduced Earth scale), Scale Factor = 1. At other places the scale factor will be other than unity, it may be more if the scale has expanded, or less if there has been compression. The difference between scale factor and unity describes the scale deviation and is expressed as a percentage change, i.e.,

$$\text{Scale Deviation \%} = (\text{Scale Factor} - 1) \times 100.$$

As an example, suppose it is necessary to find the scale and scale deviation at a point, B, where the scale factor is 1.01, and where the stated scale of the map is 1:1,000,000.

$$\text{Scale at B} = \text{Scale factor at B} \times \text{Reduced Earth Scale}$$

$$= 1.01 \times \frac{1}{1{,}000{,}000}$$

$$= \frac{1}{990{,}099}$$

or 1 in 990,099

$$\text{Scale Deviation at B} = (1.01 - 1) \times 100 = 1\%$$

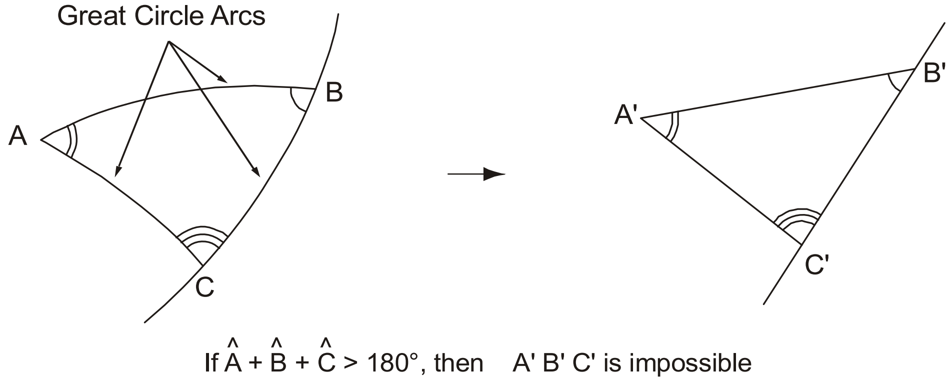
35. **Measurement of Distance**. One of the prime requirements of a map projection is that distance measurement should be simple and accurate. Since a constant scale is impossible throughout any projection the demand is realized by using charts on which the pattern of scale expansion is well defined in any direction from a point, or by using only those small sections of a given projection over which scale expansion is so small that the chart can be regarded as having a constant scale (for practical purposes a limit of ± 1% scale deviation is accepted).

Conformal Projections

36. For navigation purposes it is important that a chart should give an accurate representation of bearings; the bearing of one point from another on the Earth's surface should be represented by the same angle on the chart. This requires that at a given point on the chart the scale expansion is the same in all directions. A projection which has this property is called conformal or orthomorphic. Some of the features of conformal projections are discussed below.

37. **Representation of Great Circles**. The sum of the angles of a plane triangle is 180°, but the sum of the angles of a spherical triangle, whose sides are great circles, is always in excess of 180°; the triangle contained by two meridians and an arc of the equator has two right angles. Hence it is not possible to project all great circles as straight lines on a conformal projection (Fig 9). As with scale, however, it is often possible to use a restricted section of a projection in which all great circles are approximately straight lines.

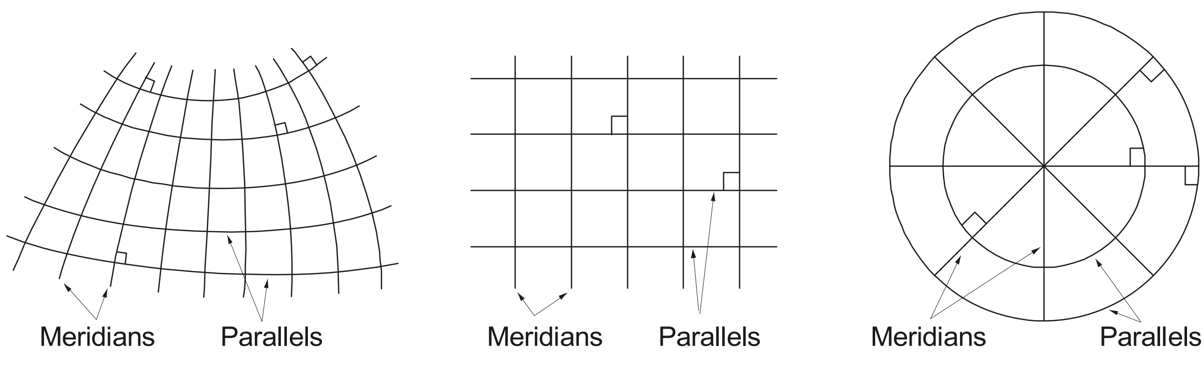
9-3 Fig 9 Great Circle as Straight Lines



38. **Representation of Rhumb Lines**. Since rhumb lines cut successive meridians at the same angle they can be represented by straight lines. Of course this does not mean that they are straight lines on all charts; indeed as a general rule they are not.

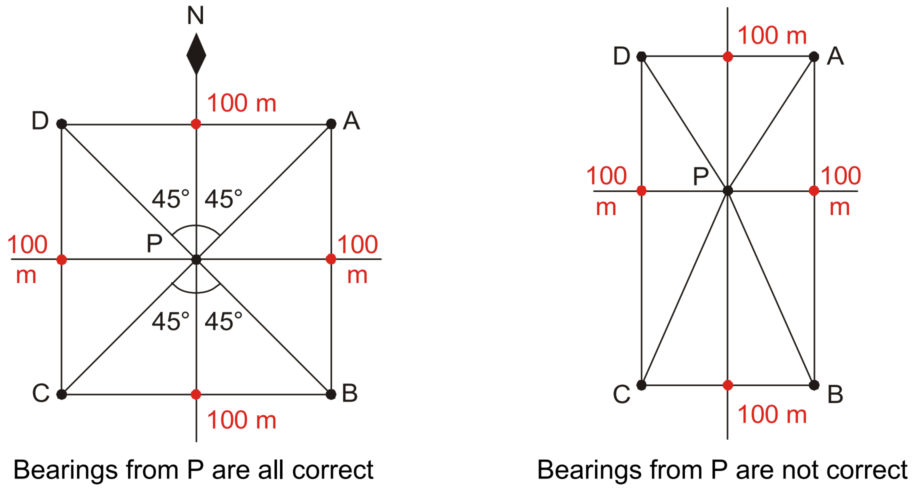
39. **Meridians and Parallels**. Since the meridians and parallels intersect at right angles on the Earth, they must intersect at right angles on a conformal projection. They need not be straight lines and Fig 10 illustrates some of the possibilities.

9-3 Fig 10 Meridians and Parallels



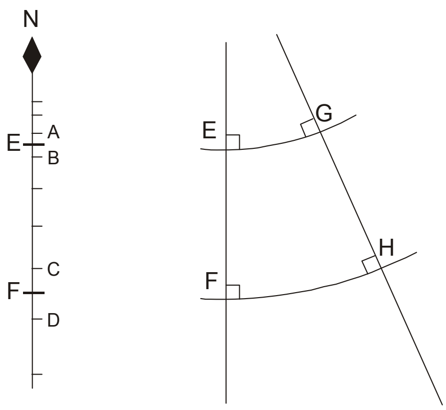
40. **Scale at a Point**. By definition scale at a point must be the same in all directions. If a point, P, and a small area around it is considered, (so small that the Earth is sensibly flat) then if 100 m to the North of P is represented by 1 mm so also must 100 m in any direction be represented by 1 mm if the compass rose at P is not to be distorted. The result of different scales in various directions is illustrated in Fig 11. It is not always possible to check scale in all directions, but if the meridians and parallels are orthogonal and scale is the same along both at a point then the chart is conformal.

9-3 Fig 11 Scale of a Point



41. **A Meaning for 'Same Scale'**. Since there has to be a scale expansion it is a useful starting point to define what it will be in one direction and then to see what must happen in other directions if the chart is to be conformal. Suppose that scale along a meridian on a given projection follows the pattern shown in Fig 12, let the mean scale over CD be 1:500, and the mean scale over AB be 1:1000. Since these values apply exactly only at points somewhere in CD and AB, suppose they apply at E and F (not necessarily the mid-points). If the chart is conformal the scales in any direction at the points E and F must be 1:1000 and 1:500, and in particular these scales apply in the directions East and West. Applying this pattern to a larger area of the chart, if on this conformal projection the parallels are concentric then the meridians must be radii of those circles. In other words the scale expansion along GH must be the same as that along EF. The scale at G must equal the scale at E, and that at H equal that at F, and so for all points on the parallels EG and FH. There can only be one conclusion, the scale must be constant along each parallel and have the value given by the expanding meridian scale at its latitude. Thus the apparent paradox that while scale expansion differs about a point, nevertheless the scale about the point is the same, is seen to be meaningful. Parallels and meridians have been considered here for simplicity. In some projections it is convenient to define different co-ordinate systems, but the same rules will apply.

9-3 Fig 12 Same Scale in all Directions

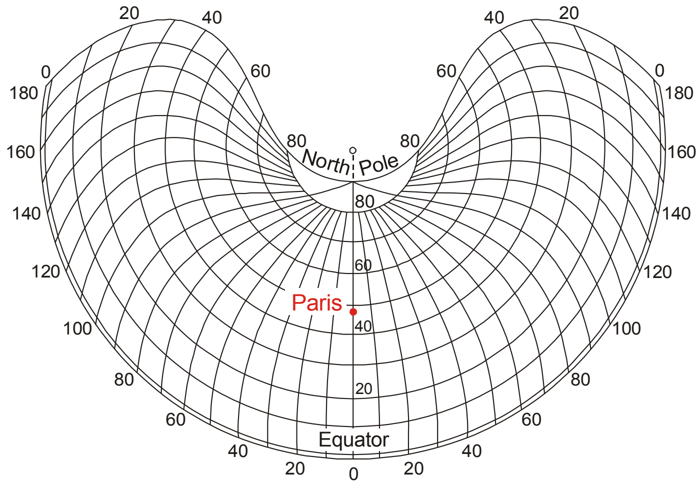


Non-conformal Projections

42. For many purposes, outside navigation, charts having properties other than orthomorphism are required. In atlases it is often useful to have a map on which areas are shown in their correct

proportion. This property is obtained by elongation, or shearing, so that scale is not the same in all directions at a point, but the product of the scales in two perpendicular directions is the same everywhere. A typical equal area, or equivalent, projection is shown in Fig 13.

9-3 Fig 13 Bonnes Equal Area Projection



43. Very few non-conformal projections are useful for navigation, but it is clearly useful to have charts on which all great circles are straight lines, or on which distances from a specified place (and no other) can be precisely measured using a constant scale. These properties can be obtained on non-conformal projections known as the gnomonic and azimuthal equidistant projections respectively.

Earth Convergency

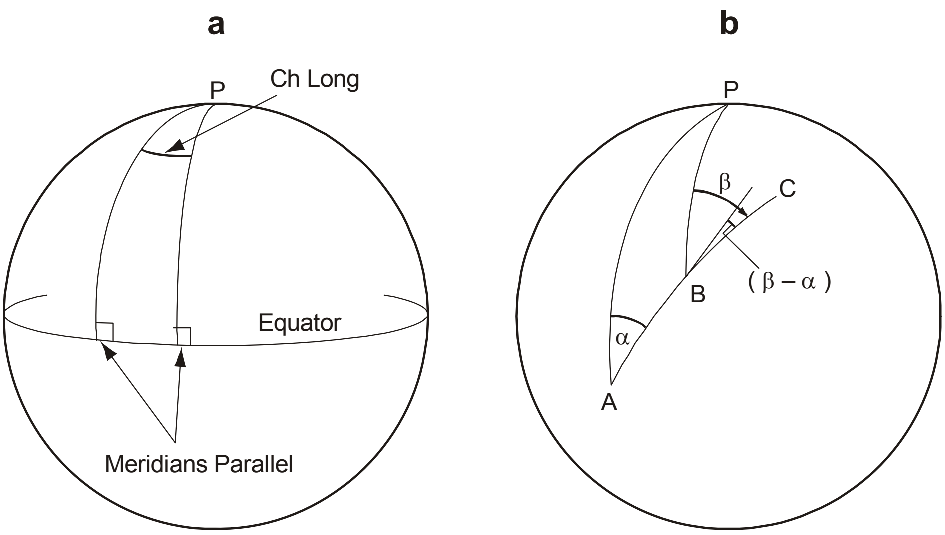
44. The angle which one meridian on the Earth makes with another is known as Earth convergency. At the poles its value is ch long (Fig 14a), but it reduces away from the pole until, at the equator where the meridians are parallel to one another, its value is 0º. If the Earth is considered as a sphere its value is given by:

Earth convergency = ch long sin lat

45. More generally this term applies to the difference in great circle bearing over two meridians. The angle $(\beta - \alpha)$ in Fig 14b is Earth convergency given approximately by:

Earth convergency = ch long sin mean lat.

9-3 Fig 14 Earth Convergency



46. Convergency, as defined in para 45, is one feature which can never be faithfully projected, for, like scale, it is a property inherent in the sphere. It describes the shape of the Earth's surface, and any map on which it is correctly shown must itself be a spherical surface.

Chart Convergence

47. The angle which one meridian makes with another on a projection is known as chart convergence. If the meridians are represented by straight lines, then chart convergence will be a constant; if the meridians are curved, it will differ from one point to another.

Definitions and Dimensions

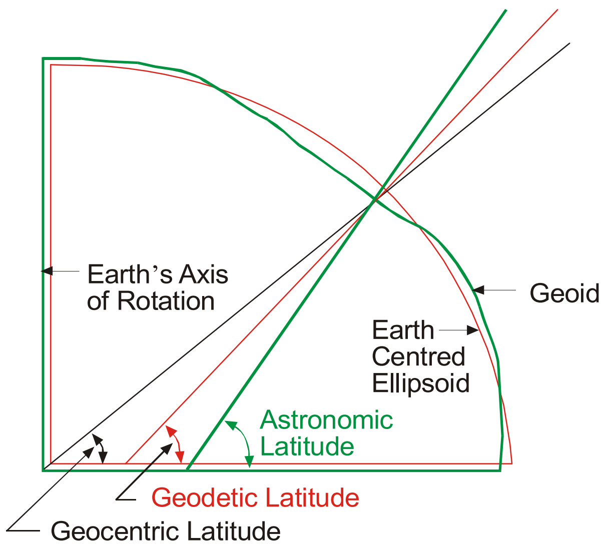
48. Depending on the degree of simplification which is applied to the shape of the Earth, so different definitions of latitude arise. These are illustrated in Fig 15 as follows:

a. **Astronomical Latitude**. On the geoid, the astronomic latitude is the angle between the vertical (the direction of gravity) at a place and the plane of the equator. It is therefore indicated by the normal to the geoid at the place.

b. **Geodetic (or Geographic) Latitude**. On an ellipsoid, the geodetic latitude is the angle between the normal to the ellipsoid meridian at a place and the plane of the ellipsoidal equator. This is the latitude plotted on navigation charts.

c. **Geocentric Latitude**. The geocentric latitude at a point is the angle made with the Earth's equatorial plane by the radius from the Earth's mass geocentre through that point.

9-3 Fig 15 Definitions of Latitude



49. In practice, when using astro, the astronomic latitude is determined (for example when a Polaris sight is taken), but the difference between this and geodetic latitude is so small that a correction is not usually applied. Geocentric latitude is useful in certain problems. If the Earth is considered as a sphere, then geodetic and geocentric latitude coincide.

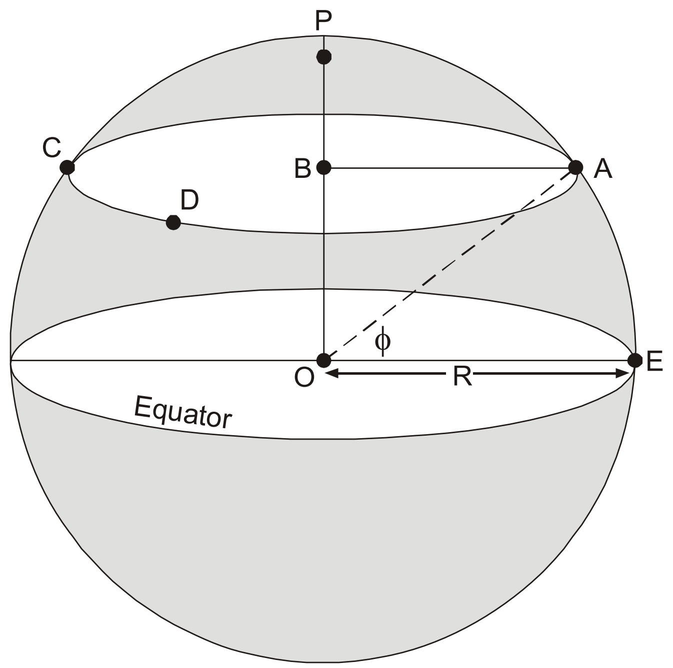
50. **Reduced Earth**. The first stage in map projection is the making of a reduced Earth to the scale required. This model can be ellipsoidal or spherical. If it is spherical then, in effect, the projected latitudes which result are corrected by the difference between the geodetic and geocentric latitudes. This difference is known as reduction of latitude; it is a quantity which also occurs when certain navigation tables based on the sphere are used. Reduction is maximum at latitude 45º when its value is about 11.6 minutes.

51. **Length of a Parallel of Latitude**. By considering the Earth as a sphere, a simple expression for the length of a parallel of latitude can be found. In Fig 16, the length of the parallel of latitude is the circumference of the circle, centre B, radius BA swept through ADC. Since:

$$\begin{aligned}
\text{Circumference} &= 2\pi r \\
\therefore \text{ length of parallel} &= 2\pi BA \\
&= 2\pi OA \cos \phi \\
&= 2\pi R \cos \phi \\
&= 2\pi R \sin (90 - \phi) \\
&= 2\pi R \sin \kappa
\end{aligned}$$

where R is the radius of the sphere, ϕ is the latitude and κ the co-latitude. By substituting R = reduced Earth's radius, the length on the model Earth can be found.

9-3 Fig 16 Length of Parallel of Latitude



52. **Arc of a Meridian - The Nautical Mile**. The nautical mile, at a given place on the Earth's surface, is the length of an arc of the meridian subtended by an angle of 1' at the centre of curvature at that place. If the Earth were a sphere, this distance would be constant, but because of the ellipticity it must clearly vary with latitude, being shorter at the equator than at the poles. An expression for the nautical mile is:

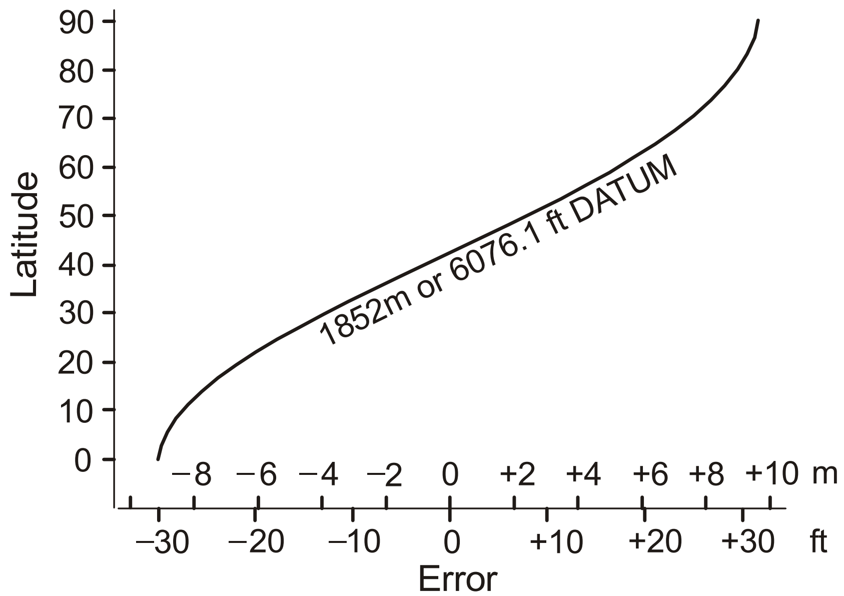
$$\text{Length of nautical mile} = 1852.9 \text{ m} \quad (9.3 \cos 2\phi \text{ metres})$$

$$\text{or} \quad 6079.2 \text{ ft} \quad (30.6 \cos 2\phi \text{ feet})$$

In practice, a mean figure is convenient and the standard adopted since 1 Mar 1971 is the International Nautical Mile = 1,852 m (6,076.1 ft) - (prior to that date the UK Standard Nautical Mile was taken to equal 6,080 ft). The 1,852 m standard is correct at about 42º 08' on the International Ellipsoid, on which the true nautical mile varies from 1,843.6 m (6,048.5 ft) at the equator to 1,862.3 m (6,109.8 ft) at the poles. When a standard unit is adopted for use within automatic instruments, some errors will accrue, as discussed below.

53. **Latitude Error**. For most practical purposes, an aircraft which flies one nautical mile is assumed to have changed its position by the length of an arc which subtends an angle at the centre of the Earth of one minute. This is not strictly accurate as the relationship between a standard nautical mile and the angle subtended at the Earth's centre varies with latitude. A graph of the difference between the International Nautical Mile and the true nautical mile is at Fig 17.

9-3 Fig 17 Errors in the Length of a Nautical Mile



54. **Height Error**. Since an aircraft will fly at a height above the surface of the earth, instruments will, in general, indicate too great a distance flown between two points as measured on the map. The discrepancy will increase with increasing height. From Fig 18 it will be seen that an arc S (representing the ground distance to be flown) subtended by an angle θ radians at the centre of the Earth of radius R is equal to R θ. For an aircraft flying at a height (h), there is a small increase in arc flown equal to δ S such that:

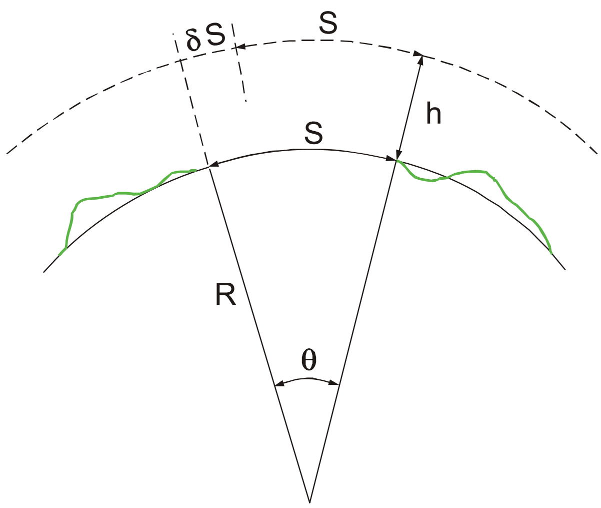
$$S + \delta S = (R + h)\,\theta$$
$$= R\,\theta + h\,\theta$$

$$\therefore \delta S = h\,\theta$$

$$\text{as } \theta = S / R$$

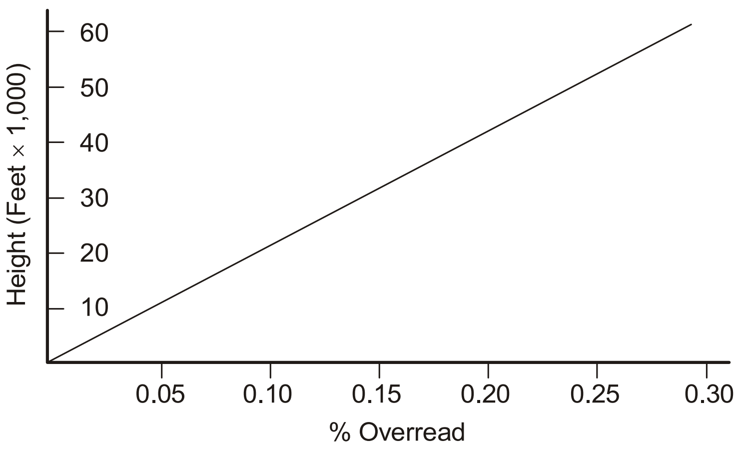
$$\delta S = \frac{h S}{R}$$

9-3 Fig 18 Height Error



A graph of the height error values for heights between 0 ft and 60,000 ft is given in Fig 19.

9-3 Fig 19 Height Error Values



Some Map Projections Compared

55. In Fig 20, a sphere has been projected by various devices. On the sphere, a man's face is outlined and his appearance is seen to alter from one projection to the next.

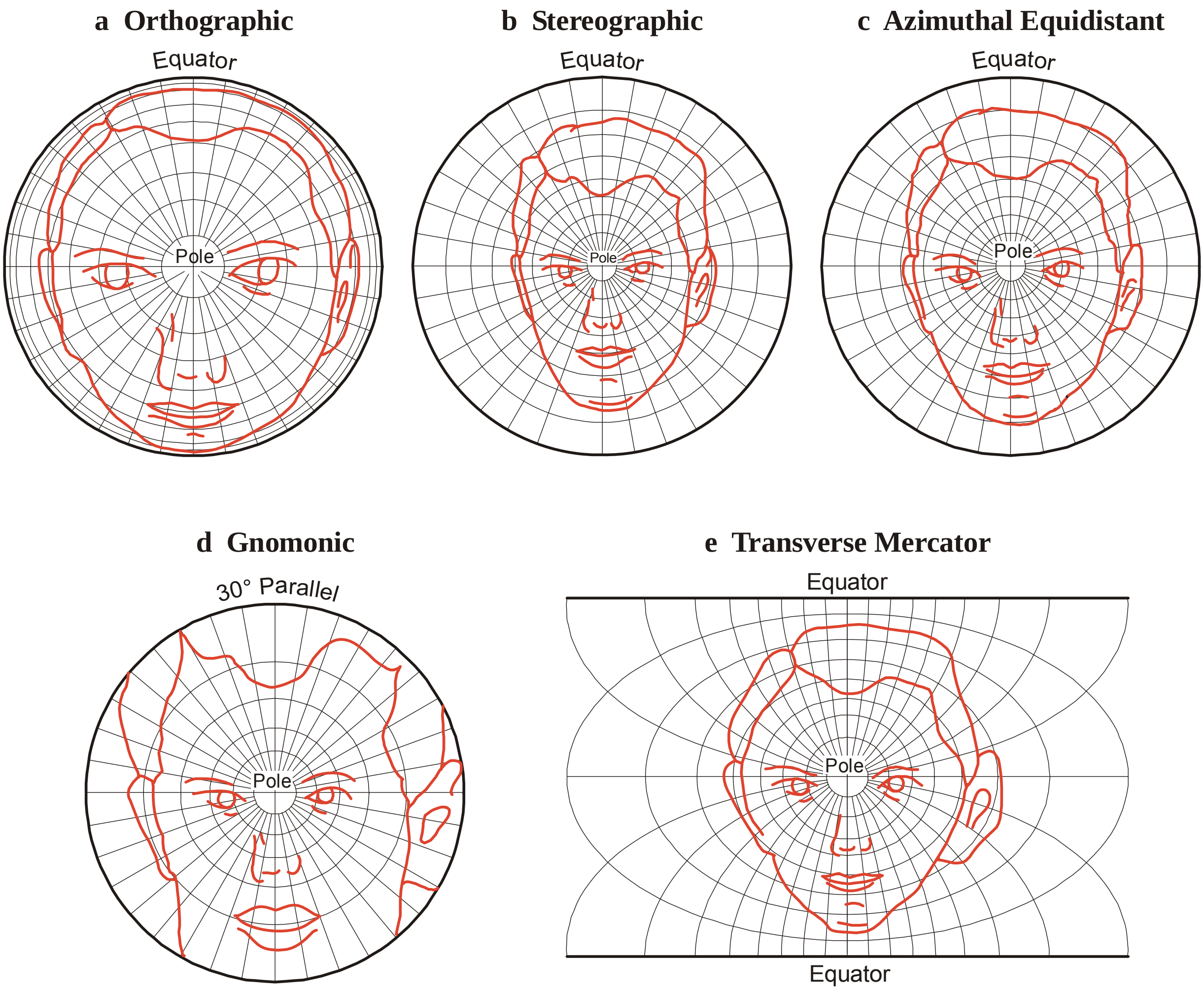
56. If the sphere is seen from an infinite distance (i.e. it is projected by parallel rays on to a flat surface) the face has the podgy look of Fig 20a. This particular projection is known as orthographic, it is neither conformal, nor equal area, nor has it any other particularly useful property, but it can be regarded as a starting point since it is how the face would appear if viewed through a telescope from a great distance.

57. Figs 20b and e are conformal projections. The bearing of one place from another (measured from the local meridian) is the same on each projection and is the same as that obtained on the surface of the sphere. It should be noted that the meridians are curved in e and straight in b, and that the face is quite different in each; Fig 20b is a polar stereographic projection, and e is a transverse Mercator projection.

58. Figs 20c and 20d, (the azimuthal equidistant and gnomonic respectively), are non-conformal projections. In c the scale is constant along all meridians, in d it expands very rapidly along the meridians, so much so that the equator cannot be shown - it is at an infinite distance from the pole. Once again the face changes.

59. These drawings illustrate the important point that none of the projections reflects what the face is really like. Each face is different, yet the similarities are sufficient to show that the same face is portrayed on each. In the same way a map projection will illustrate all the topographical features of the Earth's surface - and yet it cannot show what the surface really looks like.

9-3 Fig 20 Projections of a Sphere



AZIMUTHAL PROJECTIONS

Introduction

60. This chapter deals with one of the limiting cases of the conic projections; the azimuthal (or zenithal) projection. Unless otherwise specified, the Earth is treated as a sphere for simplicity.

61. In this case the apex angle of the cone is 180°, i.e. the projection is on to a plane tangential at a point to the reduced Earth. All projections of this type have the property that bearings from the point of tangency are correctly represented. Three types of azimuthal projection are discussed:

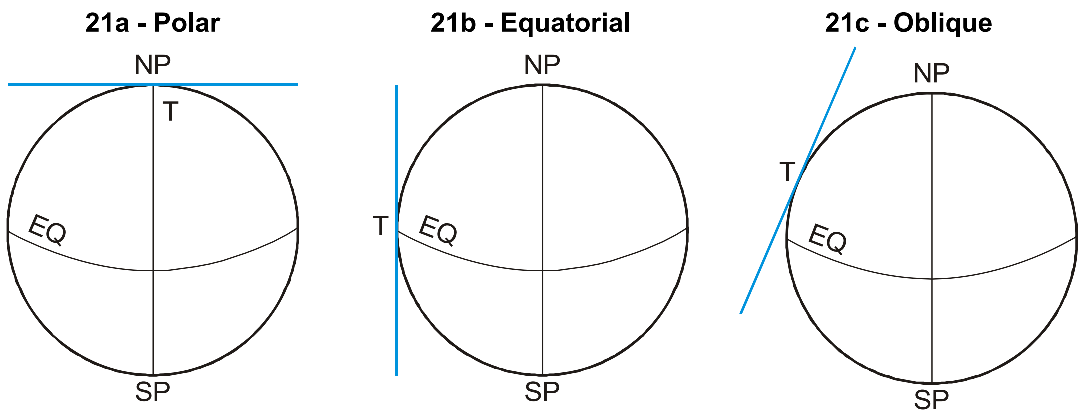
a. **The Gnomonic Projection**. The gnomonic projection is a perspective, non-conformal projection, on which great circles are straight lines.

b. **The Stereographic Projection**. The stereographic projection is conformal and perspective.

c. **The Azimuthal Equidistant**. The azimuthal equidistant projection is a non-conformal, non-perspective projection on which distances from the point of tangency are represented at a constant scale.

The plane can, in each type, be orientated to be tangential at a pole, or at the equator, or more generally in an oblique attitude as shown in Fig 21.

9-3 Fig 21 Azimuthal Projections



THE GNOMONIC PROJECTION

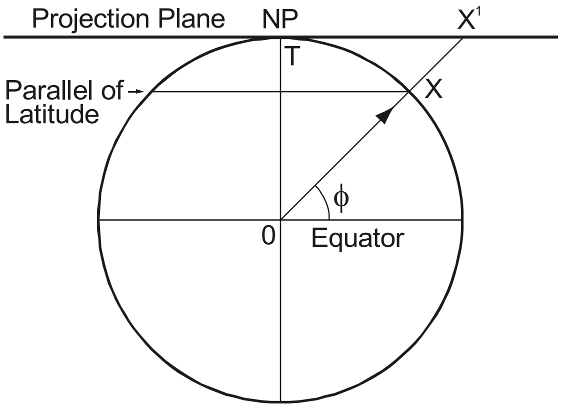
General

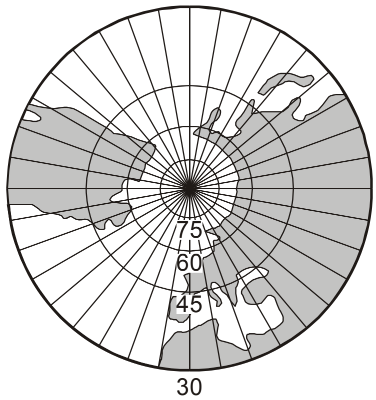
62. The gnomonic projection is perspective, the meridians and parallels being projected on to the plane surface from the centre of the sphere. It has the unique property of representing all great circles as straight lines. Scale increases away from the point of tangency, but as the scale is not the same along the meridians and the parallel at any point (except the point of tangency) the projection is not conformal.

The Polar Gnomonic

63. The point of tangency in this case is at one of the poles. The graticule is projected from the centre of the Earth (Fig 22); the parallels appear on the projection as concentric circles about the pole and the meridians are radials from the same point.

9-3 Fig 22 Polar Gnomonic





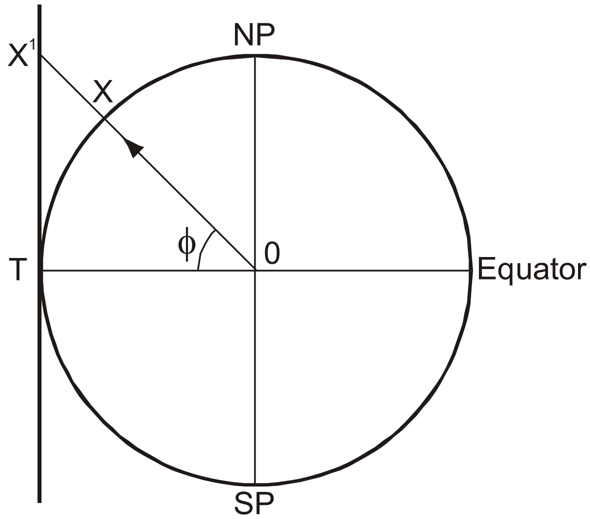
64. **Scale**. Scale increases away from the pole of tangency, but the rate of change along the meridians differs from that along the parallels. At a latitude ϕ, the scale factor along the parallel is given by sec $(90° – \phi)$ and the scale factor along the meridian by $\sec^2 (90° – \phi)$.

65. **Coverage**. This projection is limited in extent to less than 90° from the point of tangency; the equator cannot be shown since it would project as a plane parallel to the tangent plane.

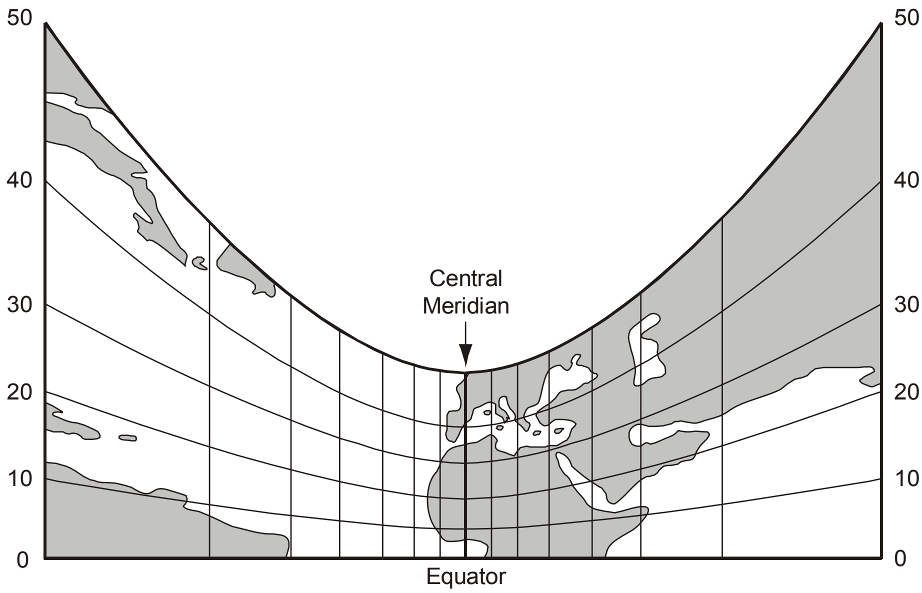
The Equatorial Gnomonic

66. The principle of projection is the same as for the polar gnomonic but in this case the point of tangency is on the equator (Fig 23). The meridians appear on the projection as parallel straight lines perpendicular to the equator, and the parallels as curves concave to the nearer pole, as shown in Fig 24.

9-3 Fig 23 Equatorial Gnomonic Projection



9-3 Fig 24 Equatorial Gnomonic Graticule

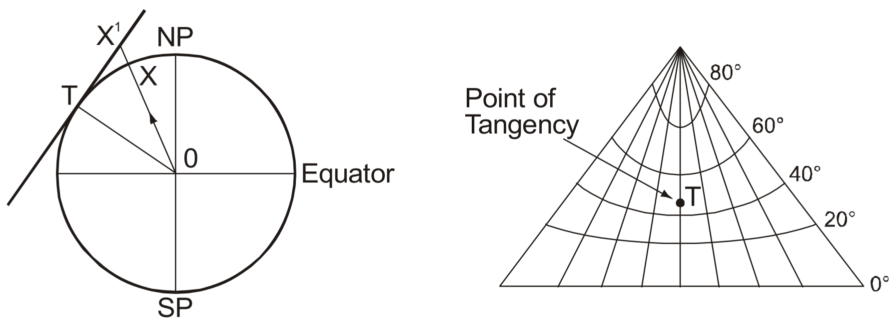


67. **Scale**. Scale increases away from the point of tangency with the same pattern as the polar case.

The Oblique Gnomonic

68. The oblique gnomonic projection uses a point of tangency at any point on the Earth other than a pole or on the equator (Fig 25). The graticule appears on the projection with the meridians as radial straight lines from the nearer pole and the parallels as curves concave to the same pole.

9-3 Fig 25 Oblique Gnomonic Projection



69. Scale, as before, expands away from the point of tangency.

Properties of Gnomonics

70. The properties of all gnomonic charts are as follows:

a. Any straight line on the projection exactly represents a great circle.

b. Bearings are correctly represented from the point of tangency, but not otherwise. The projection is not conformal.

c. Rhumb lines are curves concave to the nearer pole.

d. Coverage is limited to less than 90° from the point of tangency.

e. Scale increases away from the point of tangency.

Uses of Gnomonics

71. **Great Circle**. Great circle tracks can be found on the gnomonic chart and transferred to the plotting chart. A chart designed with this purpose in view is the Meade's Great Circle Diagram (Admiralty Chart 5029) discussed in para 75.

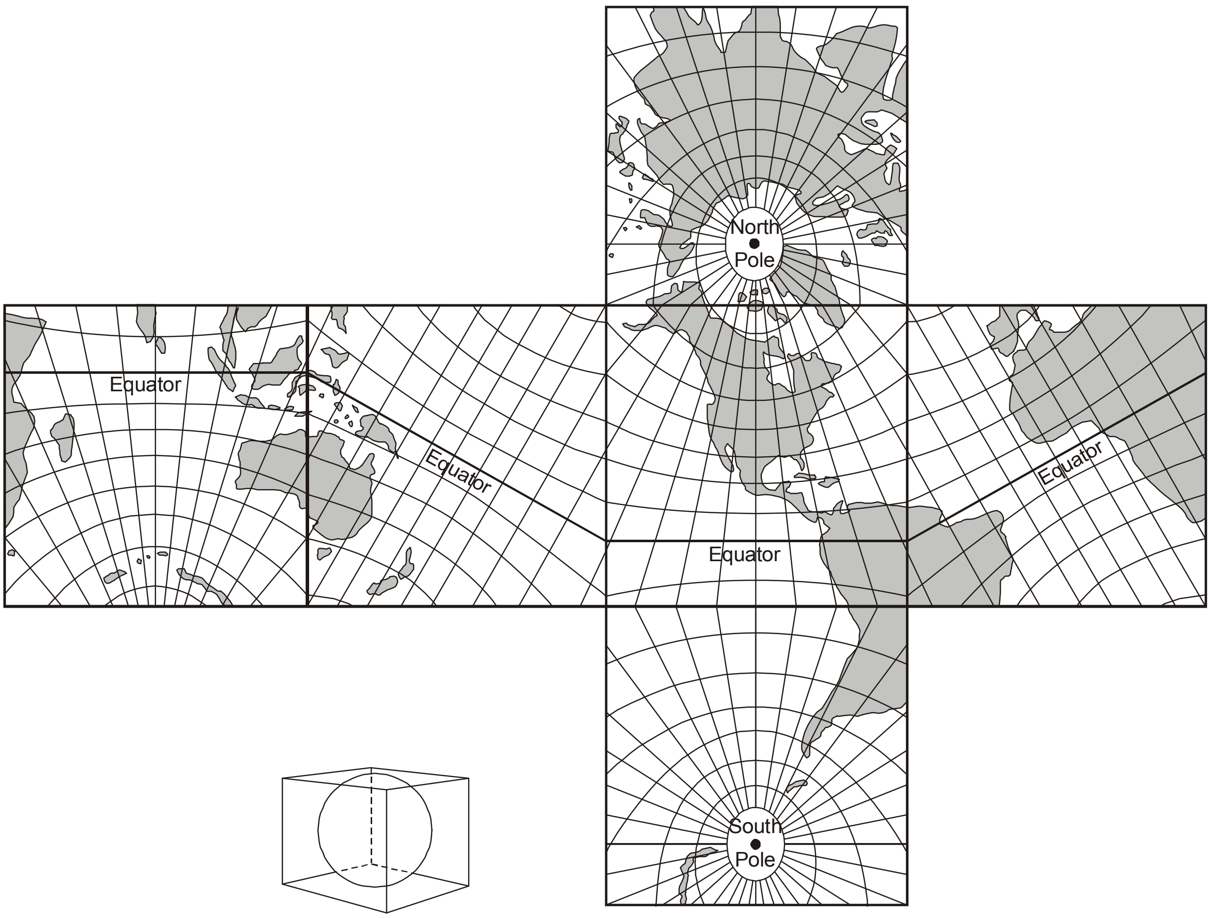
72. **Radio Bearings**. Gnomonic charts are sometimes used for D/F triangulation. The bearings (which are great circles) are passed to the master station where they are plotted on a gnomonic chart. An oblique gnomonic is used, the point of tangency being the position of the master station. The slave stations are plotted in their correct positions on the chart and offset compass roses are drawn about them to allow for distortion.

World Projection on to a Cube

73. Gnomonic projections can be used to obtain complete coverage of the world by arranging orthogonal planes around the sphere. The cube formed can be orientated to produce two polar and four equatorial projections, or six oblique projections.

74. The oblique case is illustrated in Fig 26. Care is required in using such a chart since a straight line joining positions in adjacent projection squares represents two great circle arcs which intersect on the boundary, and not the great circle joining the places.

9-3 Fig 26 Projection of the World on a Cube



Meade's Great Circle Diagram (Admiralty Chart 5029)

75. Meade's Great Circle Diagram, (Admiralty Chart 5029), is a chart on which the blank graticules of polar and equatorial gnomonic projections are shown. The polar gnomonic extends from lat 60° N or S to 83° N or S, and the equatorial gnomonic from the equator to 65° N or S. Both graticules cover 150° ch long and are graduated in degrees. The meridians on both graticules can be renumbered to any required longitude.

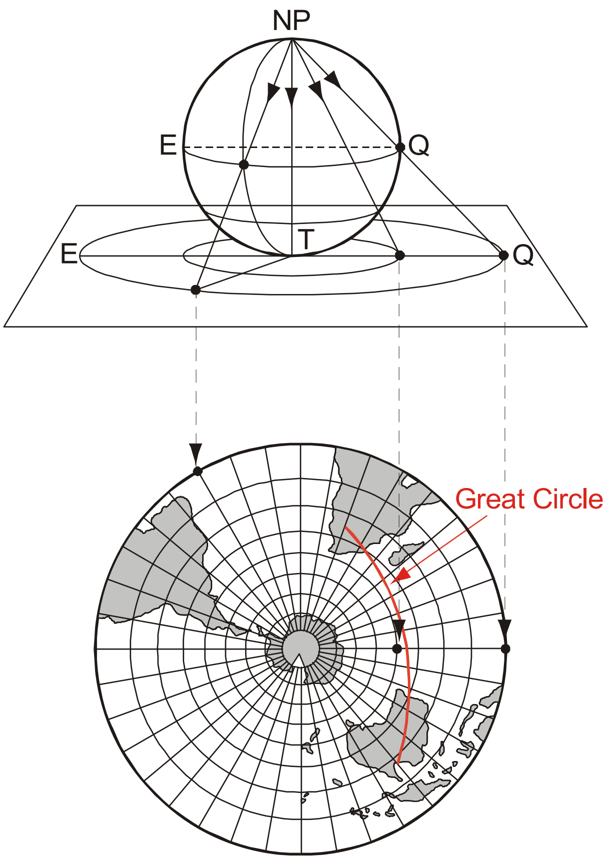
76. Since a straight line on either graticule represents a great circle, positions may be plotted on this chart and the great circle track between them transferred to the plotting chart. Full directions for use are provided on the actual diagram.

THE STEREOGRAPHIC PROJECTION

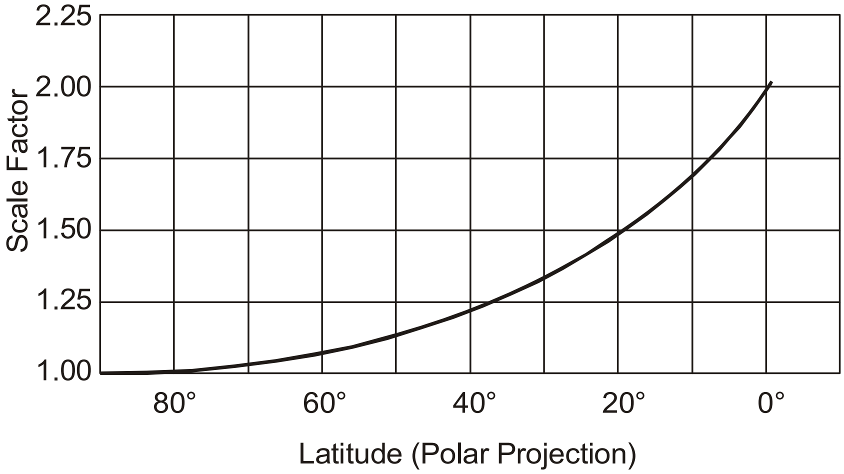
General

77. The stereographic projection is also perspective, but differs from the gnomonic by having the point of projection diametrically opposite the point of tangency instead of at the centre of the sphere (Fig 27). As with all other azimuthal projections there are three cases but only the polar case is extensively used in navigation. In the final presentation of the polar graticule, the meridians are represented by radial straight lines from the point of tangency (the pole) and the parallels of latitude by concentric circles about it. The polar stereographic projection can be extended to cover points more than 90° from the point of tangency and the equator can be shown. Scale expands away from the point of tangency along the meridians, and scale along a parallel is equal to the meridian scale at that latitude; scale is therefore the same in all directions at a point and the projection is conformal. A graph of polar stereographic scale factor is shown in Fig 28.

9-3 Fig 27 South Polar Stereographic Projection



9-3 Fig 28 Stereographic Projection Scale Factor



Properties

78. The properties of the polar stereographic are as follows:

a. Scale expands along the meridians with distance from the point of tangency.

b. The scale at any point is the same along its meridian and parallel; the projection is therefore conformal.

c. All meridians are projected as straight lines; all other great circles are represented by arcs of circles, but because of the large radii they are not usually easy to plot. Near the pole the great circle and the straight line are almost coincident.

d. A rhumb line is a curve concave to the pole of tangency.

e. Scale may be taken to be constant near the pole of tangency (scale deviation is less than 1% above latitude 78.5°).

f. It can be extended to cover a whole hemisphere or more.

g. The constant of the cone (n) = 1.

Plotting of Radio Bearings

79. The plotting of radio bearings on a polar stereographic is simple near the pole since the divergence of the straight line from the great circle is very small. This divergence, Δ, is given by:

$$\Delta = \tfrac{1}{2} \text{ ch long (sin mean lat} - n)$$

Typical values of Δ are:

ch long	mean lat	Δ
10º	75º	0.17º
20º	75º	0.34º
35º	85º	0.066º

These divergences are too small to be of any significance using ordinary plotting instruments, and, providing the chart is not used below, say, 75° no correction need be applied.

Uses

80. The common uses of the polar stereographic are:

a. Polar plotting charts.

b. Topographical maps of polar regions.

THE AZIMUTHAL EQUIDISTANT PROJECTION

General

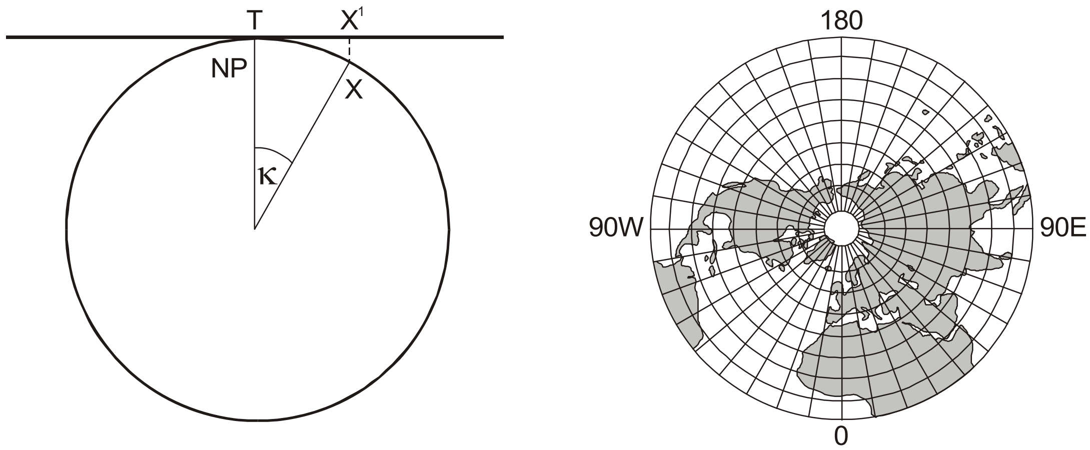
81. This is not a perspective projection; it is drawn so that all distances from the point of tangency are correct to scale. On this type of projection the bearing and distance of any point may be measured correctly from the point of tangency. Only the polar and oblique projections of this type are discussed; remarks made on the oblique case apply equally to the equatorial case.

The Polar Equidistant

82. The point of tangency is the pole and the graticule presents the meridians as radial straight lines from the point of tangency and the parallels as equally spaced concentric circles about that point (Fig 29). The scale along the meridians is constant but along the parallels is given by:

$$\frac{K \text{ radians}}{\sin K} \qquad \text{Where } K = \text{co - lat}$$

9-3 Fig 29 Polar Equidistant Projection



83. **Properties**.

a. The scale along the parallels increases with distance from the pole. Scale along the meridians is correct. Scale errors are small provided the projection does not extend far from the pole (1% scale deviation at about 84°).

b. It is not conformal.

c. Except for meridians, a straight line does not represent a great circle.

d. The whole world can be represented on a single projection.

84. **Uses**.

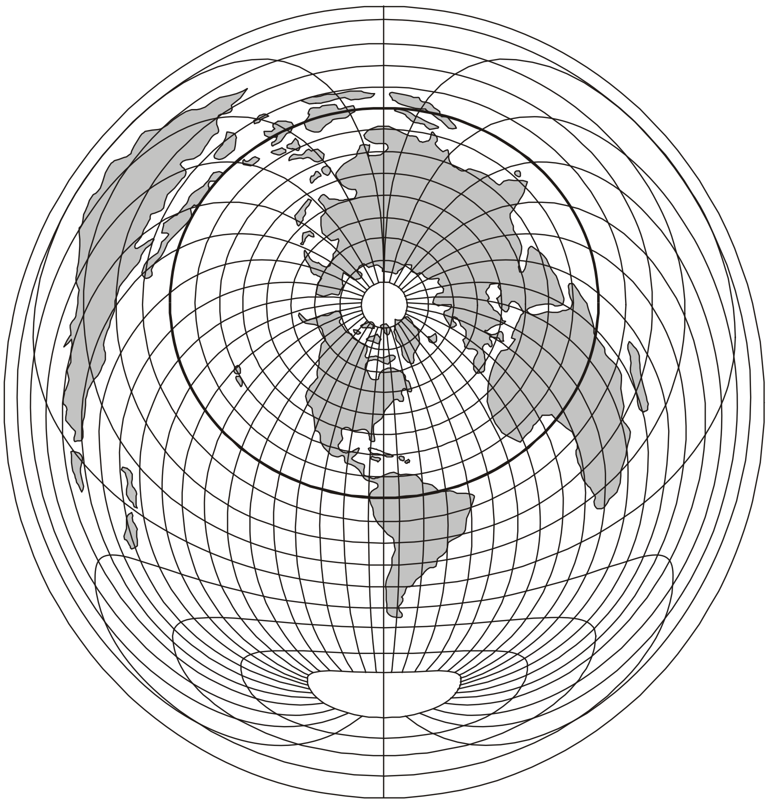
a. Admiralty maps of polar regions.

b. Star maps, including Sky diagrams of Air Almanacs.

Oblique Azimuthal Equidistant

85. The graticule for the oblique azimuthal equidistant projection is difficult to construct and complicated in appearance (Fig 30). The chart is constructed using the bearings and distances of required points from the point of tangency.

9-3 Fig 30 Oblique Azimuthal Equidistant Projection



86. **Properties**.

a. Scale along radials from the point of tangency is constant. In other directions, scale variation is complicated and measurement very difficult.

b. Straight lines passing through the point of tangency are great circles. A straight line elsewhere does not represent a great circle.

c. It is not conformal.

d. The whole world can be shown on the projection.

87. **Uses**.

a. **Maps for Strategic Planning**. The projection is based on a point of importance. Concentric circles from this point show correct ranges which could represent, for example, radii of action.

b. **Civil Uses**. For example, a projection based on the position of a radio transmitter will show the great circle distance and bearing of any receiver in the world.

CYLINDRICAL PROJECTIONS

Introduction

88. The cylindrical projections are those in which the apex angle of the cone is zero; the cone becomes a cylinder tangential to the reduced Earth along a great circle and the meridians and parallels are projected onto it. When developed the great circle of tangency is shown as a straight line as are all great circles orthogonal to it. The poles of the projection, those points removed 90° from the great circle of tangency, cannot be shown on most projections of this type.

89. When the great circle of tangency is the equator the projection is known as a normal cylindrical; when it is other than the equator it is a skew cylindrical.

SIMPLE NORMAL CYLINDRICALS

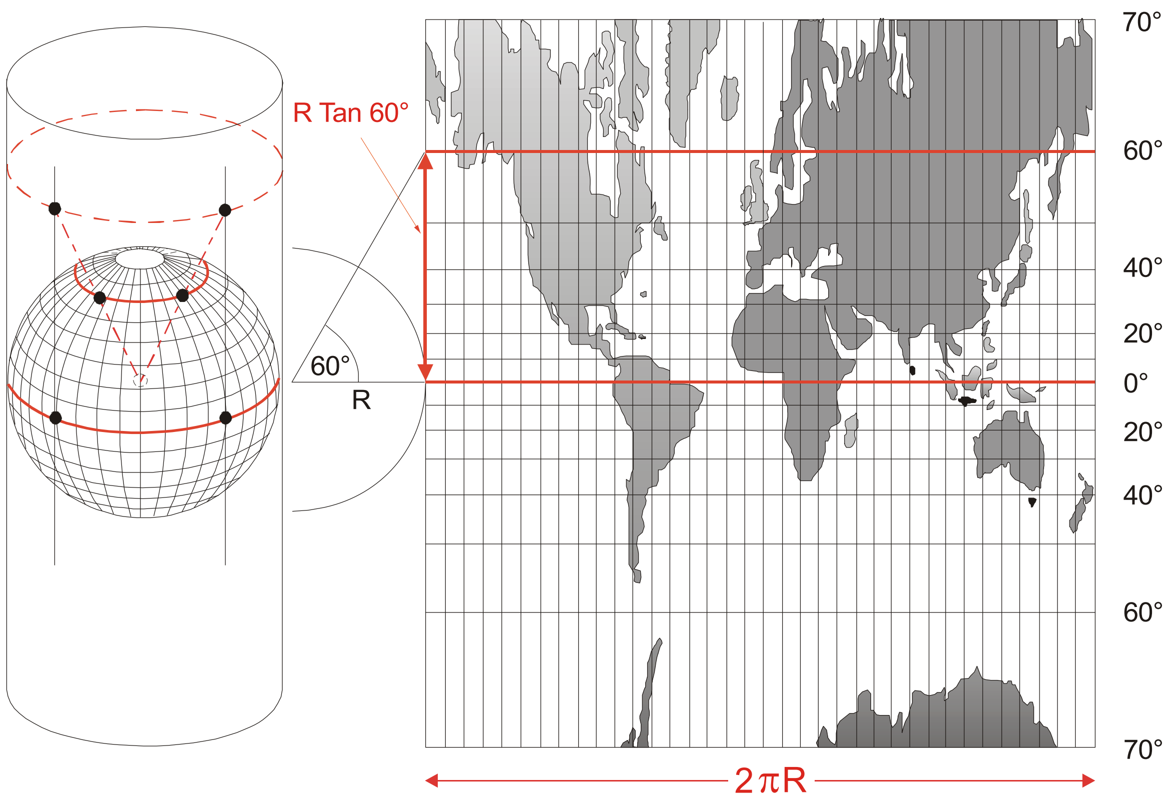
General

90. Two simple normal cylindrical projections are discussed; the first is perspective, the second non-perspective.

Geometric Cylindrical Projection

91. The geometric cylindrical projection is provided by a light source at the centre of the reduced Earth which projects the parallels and meridians on to a cylinder wrapped around the reduced Earth and tangential at the equator. The developed projection shows the equator as a straight line of length equal to the equatorial circumference of the reduced Earth. The meridians are parallel straight lines at right angles to the equator while the parallels of latitude are straight lines parallel to the equator and of length equal to it. The general appearance is shown in Fig 31, where it can be seen that the meridian spacing at the equator is the actual reduced Earth spacing.

9-3 Fig 31 Geometrical Cylindrical Projection



92. Since the equator of the reduced Earth has length 2πR, so the equator and all parallels are of length 2πR on the chart. The parallels are drawn (Fig 1) at heights above or below the equator given by R tan ϕ, and it is clear from this, and from Fig 30, that latitudes 90° N and 90° S cannot be shown.

93. **Scale**. Scale factor along the parallels is equal to the secant of the latitude. Along the meridians scale factor can be shown to equal the square of the secant of the latitude.

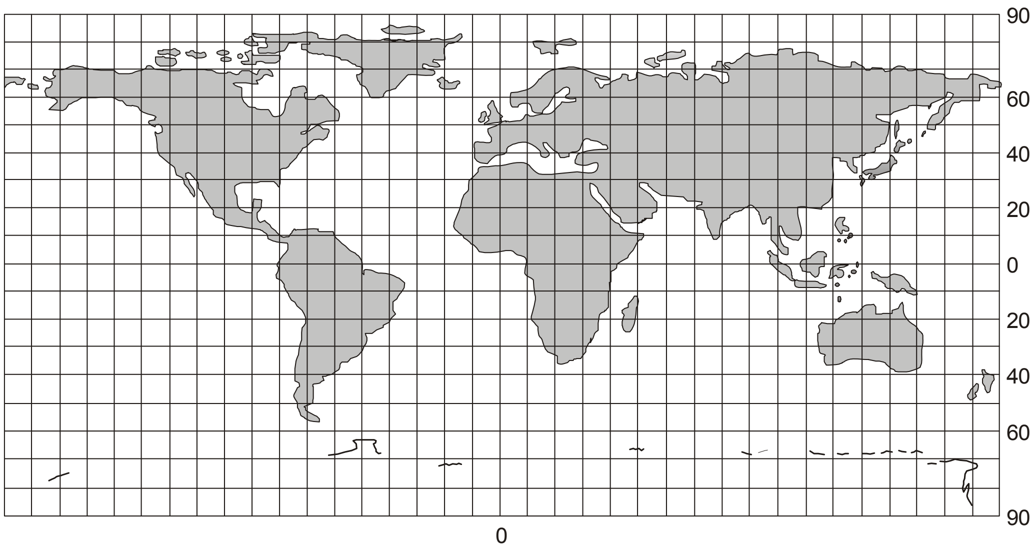
94. **Properties**. Since scale increases at one rate along the meridians and at another along the parallels the projection is not conformal. Further, the difference in scale expansion means that it is very difficult to measure intercardinal directions. The chart is not equal area, nor indeed has it any useful property beyond its simplicity.

Equidistant Cylindrical Projection

95. The equidistant cylindrical projection, also called the Plate Carree, is non-perspective, but is like the geometric cylindrical in some ways. The equator is represented by a straight line of length 2πR. The meridians are shown as parallel straight lines at right angles to the equator, at intervals on it equal to the reduced Earth interval. The parallels of latitude are straight lines parallel to the equator and of length 2πR.

96. The difference between the two charts lies in the heights above or below the equator at which the parallels of latitude are drawn. In the equidistant cylindrical, they are erected at their actual reduced Earth distance from it; thus 40° N is drawn at a scale distance of 2,400 nm from the equator. The complete sphere can be projected, the poles being represented by straight lines at a scale distance of 5,400 nm from the equator. The graticule appearance is shown in Fig 32.

9-3 Fig 32 Equidistant Cylindrical



97. **Scale**. Scale factor along the meridians is clearly 1, since the parallels are laid down at correct distances from the equator. Along the parallels scale factor is the same as that on the geometric cylindrical, sec ϕ.

98. **Properties**. This chart was much used by navigators prior to the sixteenth century. Scale is correct and constant along the equator and meridians, and is reasonably constant between 8° N and 8° S; beyond this the expansion along the parallels exceeds 1%, and the measurement of distance is difficult. The chart is neither conformal nor equal area, but it has the advantage of projecting the complete sphere.

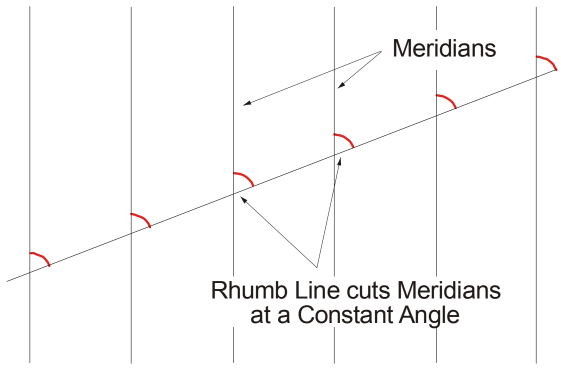
MERCATOR'S PROJECTION

Orthomorphic Cylindrical Projection

99. An orthomorphic, or conformal, projection is one on which angles, and therefore the shapes of elementary areas, are correct. Such a projection will result if the meridians and parallels are drawn at right angles and if the scale along the meridians is made to be the same as that along the parallels.

100. On the geometric cylindrical and on the equidistant cylindrical, the meridians and parallels are at right angles and the scale factor along the parallels in each case is sec ϕ. If the scale factor can be made to equal sec ϕ along the meridians, the new projection will be conformal. This is precisely the method adopted in Mercator's projection which, because it provides straight rhumb line tracks, remains one of the most important projections for navigation charts (see Fig 33).

9-3 Fig 33 Rhumb Line

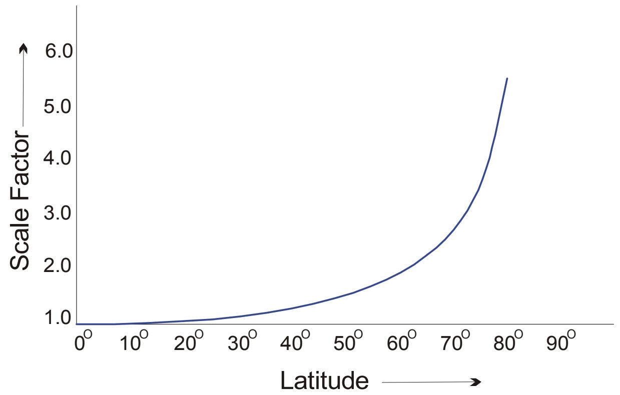


101. **Appearance of Graticule**. The final projection is very like the geometric cylindrical projection. T e equator is a straight line equal in length to the reduced Earth equator; the meridians are straight lines mounted on the equator at right angles to it and spaced upon it at reduced Earth spacing; the parallels of latitude are straight lines parallel to the equator and of length equal to it. The parallels are drawn in at heights above and below the equator which are a little less than on the geometric projection, but the poles remain at infinity and cannot appear on the projection.

Scale

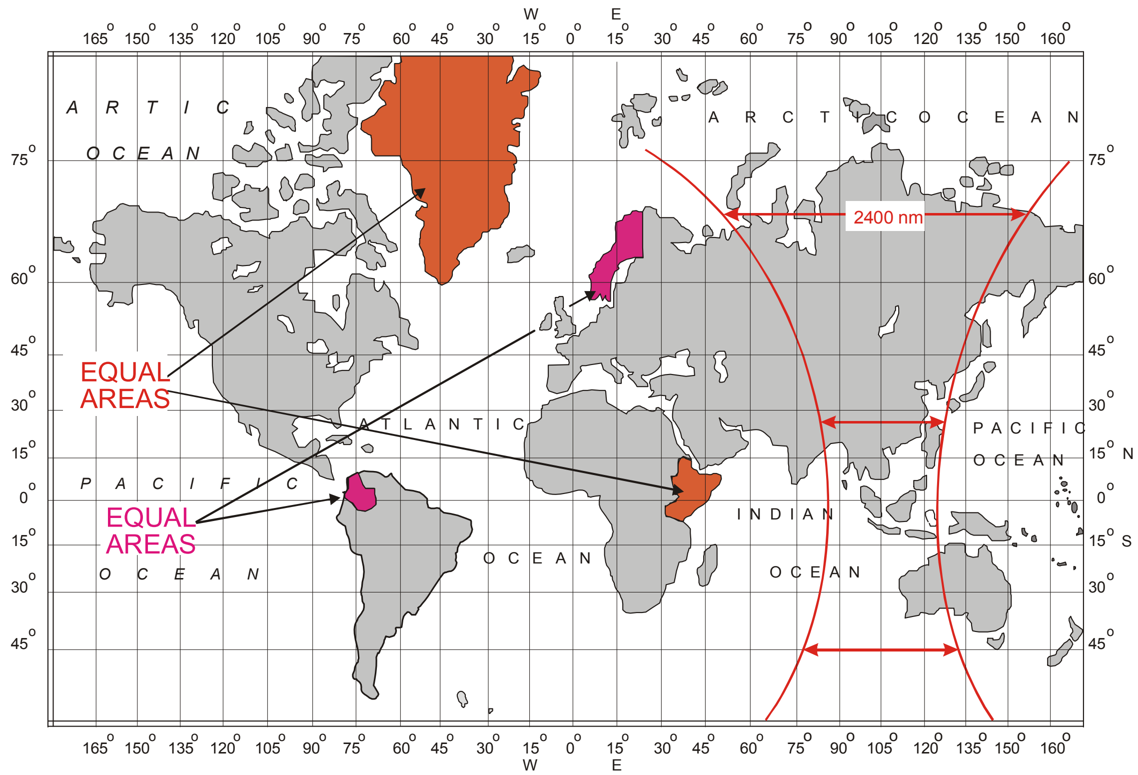
102. Scale factor along the parallels of latitude can be derived as sec ϕ. A graph of Mercator scale factor is shown in Fig 34.

9-3 Fig 34 Scale Factor



103. The distortion of areas and the excessive scale expansion away from the equator, characteristic of the Mercator projection, are illustrated in Fig 35.

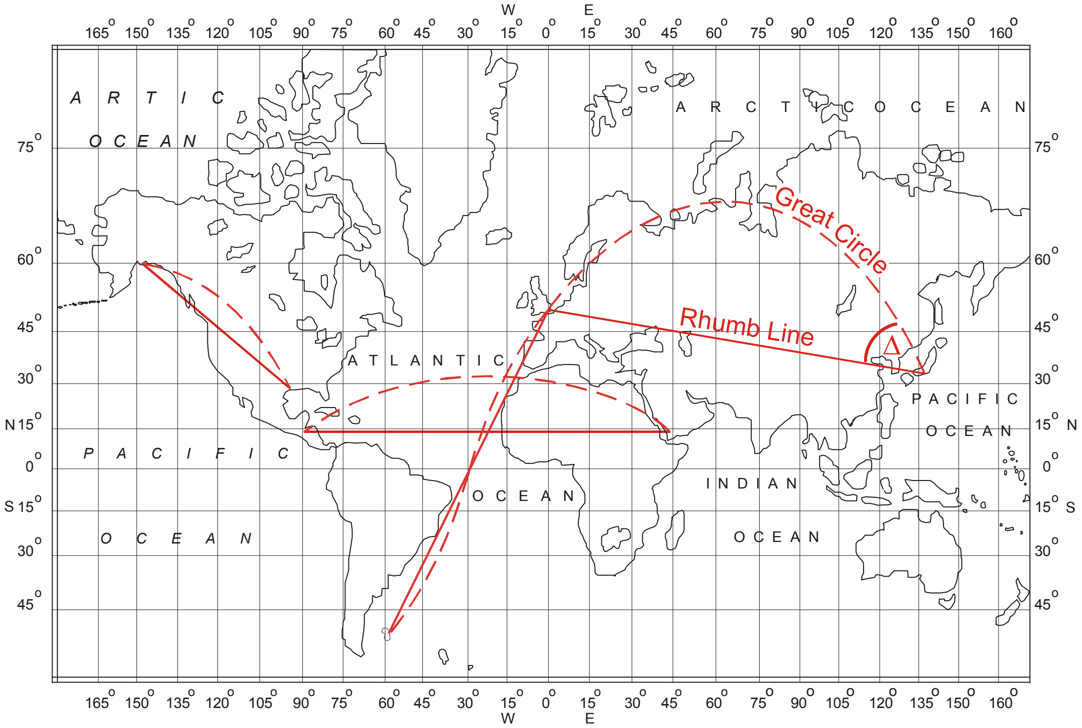
9-3 Fig 35 Distortion of Mercator Projection



Great Circles

104. Only the equator and the meridians are projected as straight lines; all other great circles appear as curves concave to the equator. Some examples are shown in Fig 36.

9-3 Fig 36 Great Circle and Rhumb Lines



105. **Conversion Angle**. In Fig 36, the angle (Δ) between the straight line and the great circle is known as conversion angle. The projected great circle is not an arc of a circle, and strictly speaking, the angle Δ is not the same at each end, unless the end points are at the same latitude. Nevertheless if the change of latitude is small they can be assumed to be equal and can be given the value
½ ch long × sin mean lat

106. **Great Circle Tracks**. The great circle route is, of course, a shorter distance than the straight rhumb line route, but the difference is small enough to be ignored in equatorial regions (12° N to 12° S). In other latitudes, when the distance exceeds about 1,000 nm it is best to examine the great circle by transferring points from a gnomonic projection or by calculation, to discover if a significant economy can be made.

Measuring Distances

107. Distances must be measured using the scale at the given point, since scale expands with latitude. Acceptable results are obtained by splitting the line to be measured into 100 to 200 nm sections and using the latitude scale at the mid point of each section for its measurement.

Uses

108. The main feature of the Mercator is that straight lines are rhumb lines. For this reason the Mercator will probably remain one of the most popular plotting and topographical charts in equatorial regions.

109. Near the equator the Mercator chart is the optimum projection. Scale may be considered constant within 8° of the equator, and a straight line in any direction, although still a rhumb line, is almost a great circle.

110. In middle and high latitudes, the Mercator projection is not the best available, because of the difficulty of precise distance measurement, the extravagance of rhumb line flight paths, and the problem of determining great circles. It is impossible to use the Mercator projection for polar flights.

Summary of Properties

111. The properties of the Mercator may be summarized as follows:

a. Scale is correct only along the equator; elsewhere it increases as the secant of the latitude.

b. Because the secant of 90° is infinity, the poles cannot be shown.

c. A straight line represents a rhumb line.

d. A great circle (apart from the equator and the meridians) is represented by a curved line convex to the nearer pole. Great circles near the equator are satisfactorily represented by straight lines.

e. The projection is conformal. It is not equal area and areas are greatly exaggerated in high latitudes.

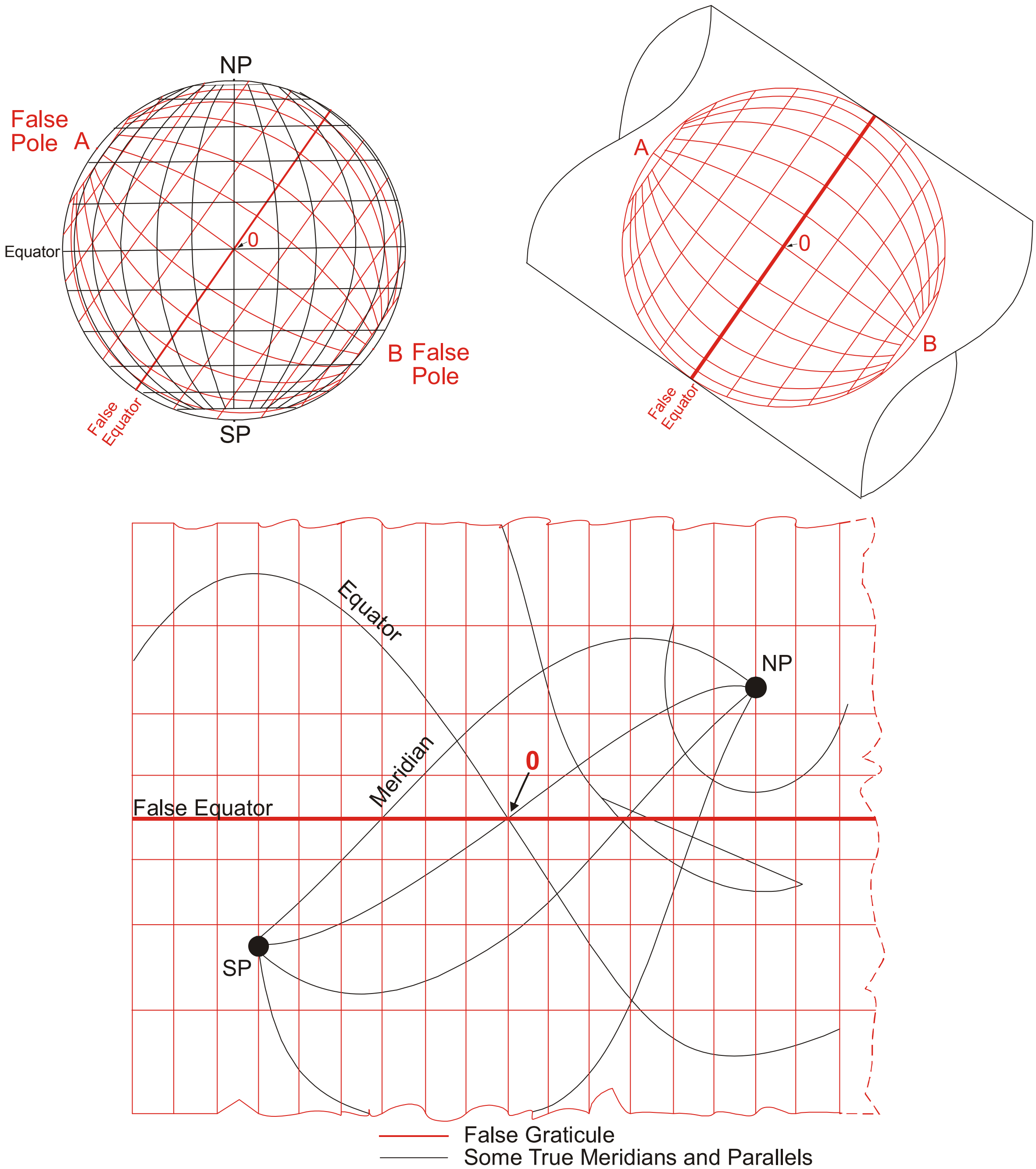
SKEW CYLINDRICALS

Technique of Construction

112. Skew cylindrical projections are the derivatives of the perspective projections which would be obtained using a light source at the centre of the reduced Earth to cast shadows onto cylinders wrapped around it, and tangential at great circles other than the equator. The simplest interpretations of such projections is obtained by erecting a false graticule of meridians and parallels on the reduced Earth; the great circle of tangency becomes the false equator, and false meridians are drawn as great circles at right angles to the false equator. The false meridians intersect at false poles.

113. The false graticule is projected onto the cylinder which is then developed. Some points of intersection of geographical latitude and longitude with the false graticule are computed, plotted on the projection and joined by smooth curves. These are labelled in geographical coordinates and the false graticule erased. The process is illustrated in Fig 37.

9-3 Fig 37 Construction of a Skew Cylindrical



114. The type of projection required will determine the method of transformation of the false graticule onto the flat sheet, but whatever type is required the relationship between points on the geographical graticule and on the false graticule will be the same.

115. The false latitude is measured along the false meridian from the false equator to the point; the false ch long is measured from some convenient datum false meridian (the false meridian through the intersection of the equators is often chosen with the alternative of that joining the false and geographic poles).

116. The skew cylindrical projections which are important in navigation are the Mercator projections of the false graticule. Referred to this graticule they have exactly the same properties as the normal

Mercator, but when referred to the geographical graticule the picture changes and extra care is needed. The projections considered here are:

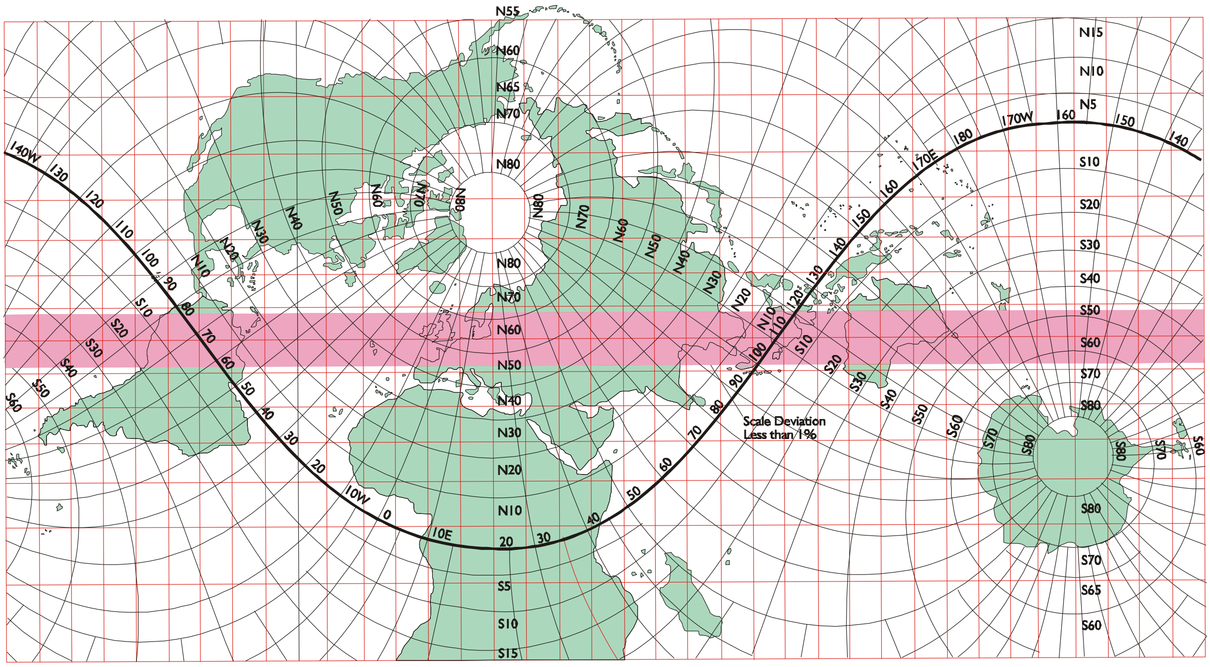
a. The Oblique Mercator.

b. The Transverse Mercator.

The Oblique Mercator

117. A diagram of an oblique Mercator projection is shown in Fig 38. Considering the false graticule, at any point, scale is the same in all directions (scale factor is the secant of the false latitude) and the rectangular spherical graticule is transformed to a rectangular plane graticule. Hence the projection is orthomorphic.

9-3 Fig 38 Oblique Mercator Projection



118. Analogously with the normal Mercator, scale can be considered constant within a false latitude band ± 8° about the false equator (the light red band in Fig 38). Since the false graticule does not appear on the final chart it is more usual to talk of a distance band of 960 nm within which scale is almost constant.

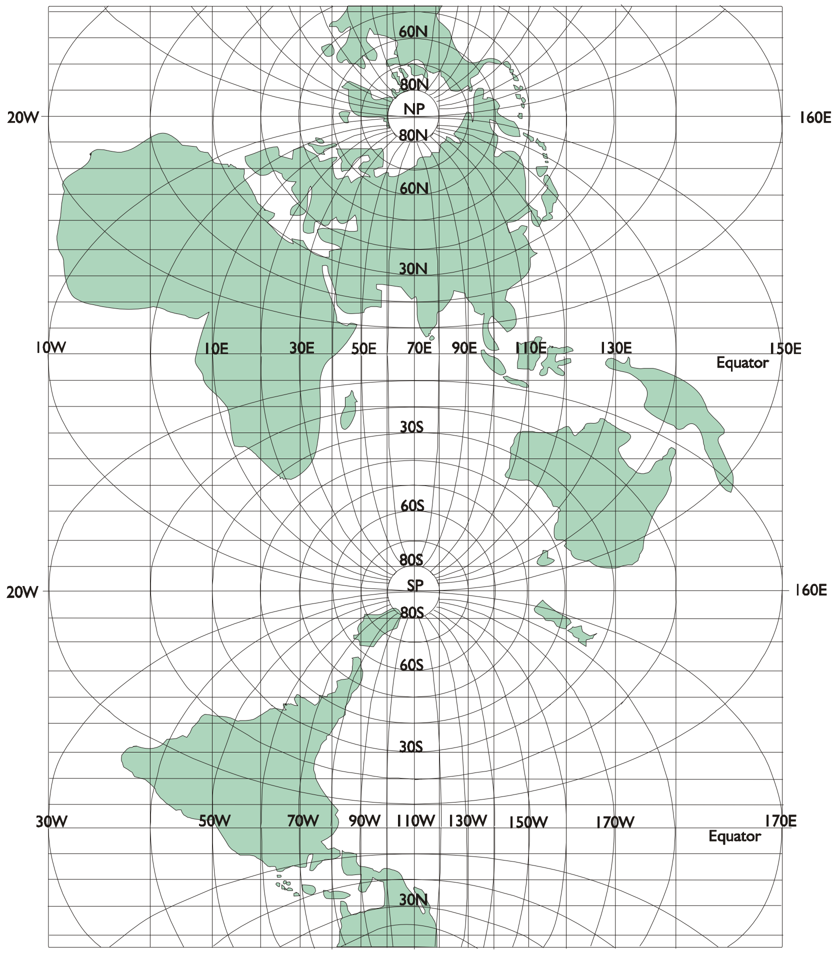
119. Because the projection is almost constant scale in this band, and is in any case conformal, it makes a useful chart for navigation along established great circle routes. Another common use is the mapping of countries of considerable length but of limited width, whose longitudinal axis does not run north/south or east/west. However the complicated appearance of the geographical graticule, together with the large scale expansion away from the great circle of tangency, limits the use of this chart.

120. Great circles are curved lines concave to the great circle of tangency, unless they happen to coincide with that great circle or are at right angles to it (false meridians). Rhumb lines are complicated curves. Straight lines on the chart represent lines along which heading measured from the false meridians is constant. Straight lines within about 500 nm of the false equator are roughly great circles.

The Transverse Mercator

121. The Transverse Mercator is the special case of the oblique Mercator in which the great circle of tangency is a meridian. The general appearance of the geographical graticule is less complicated (Fig 39) and it is easier to use for general navigation. The chart is conformal and the scale expansion varies (for a spherical Earth) with the secant of the false latitude, ie the angular distance east or west of the selected meridian of tangency.

9-3 Fig 39 Transverse Mercator Projection



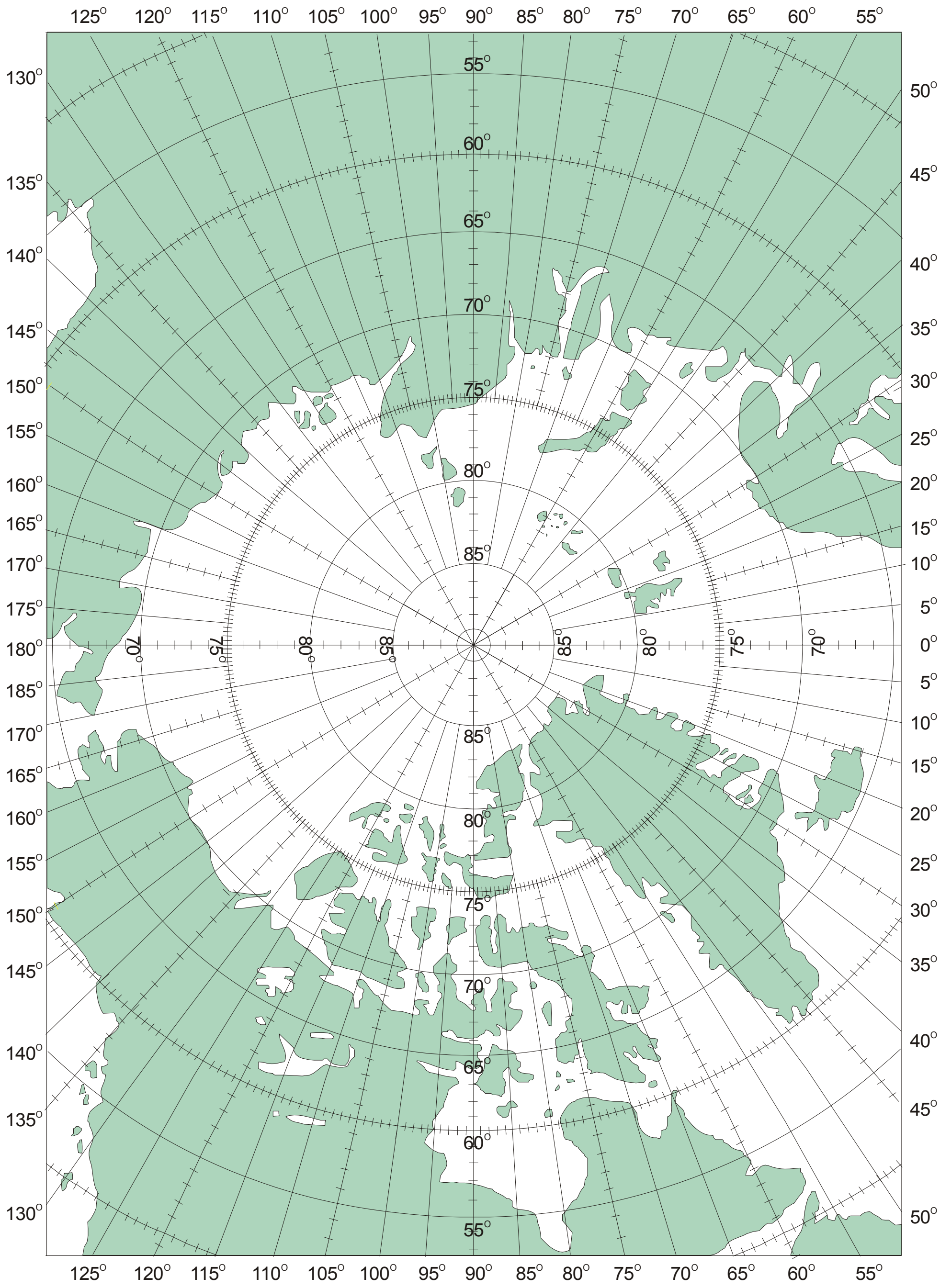
122. The projection is often used to map countries of considerable latitude extent but of little girth. If the meridian of tangency is chosen to be the mean longitude of the country then in a band some 960 nm wide disposed about this meridian, all the useful features of a normal Mercator about the equator appear. In this band the scale deviation does not exceed 1%, great circles are almost straight lines and area distortion is minimal; add these properties to conformality and a fairly regular geographical lattice and the result is an almost ideal chart.

123. The latitude extent which can be projected with these almost ideal properties is not limited. Both geographical poles and the 960 nm 1% scale deviation band about any meridian and its anti-meridian can be projected onto one sheet of paper. Some of the charts in common use are discussed below.

124. **Polar Charts**. Transverse Mercator projections in the polar regions appear very similar to the polar azimuthal charts since near the pole the parallels are nearly circular and the meridians almost straight lines (see Fig 40). Comparison with Fig 39, however, identifies both the parallels and the meridians as

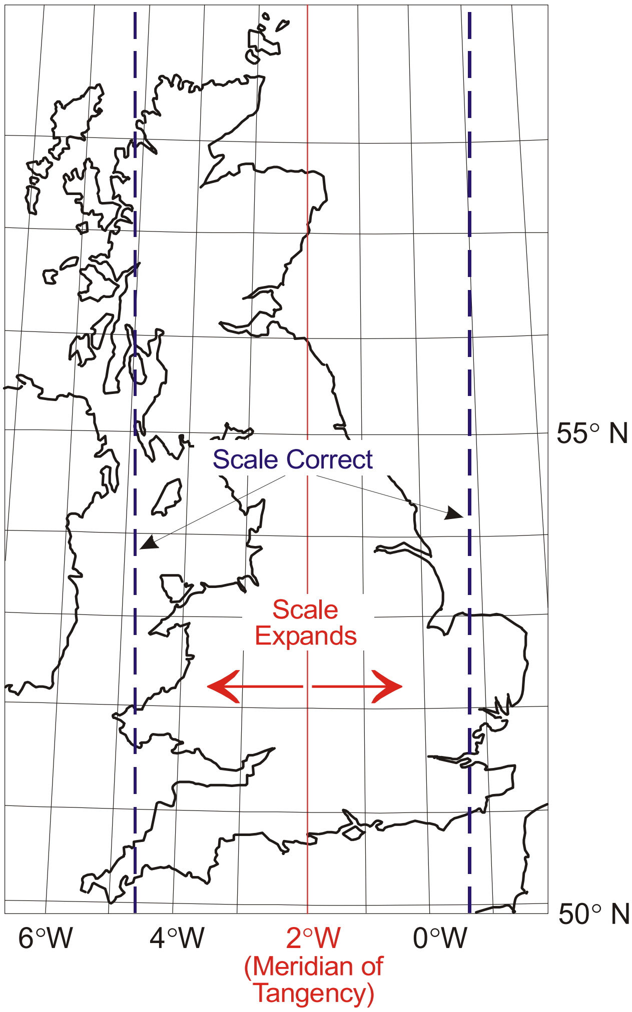
elliptic. Polar sheets on this projection are often rectangular, the greater length being provided along the line of tangency; scale errors limit the extent of the sheet at right angles to this direction.

9-3 Fig 40 Polar Chart on Transverse Mercator Projection



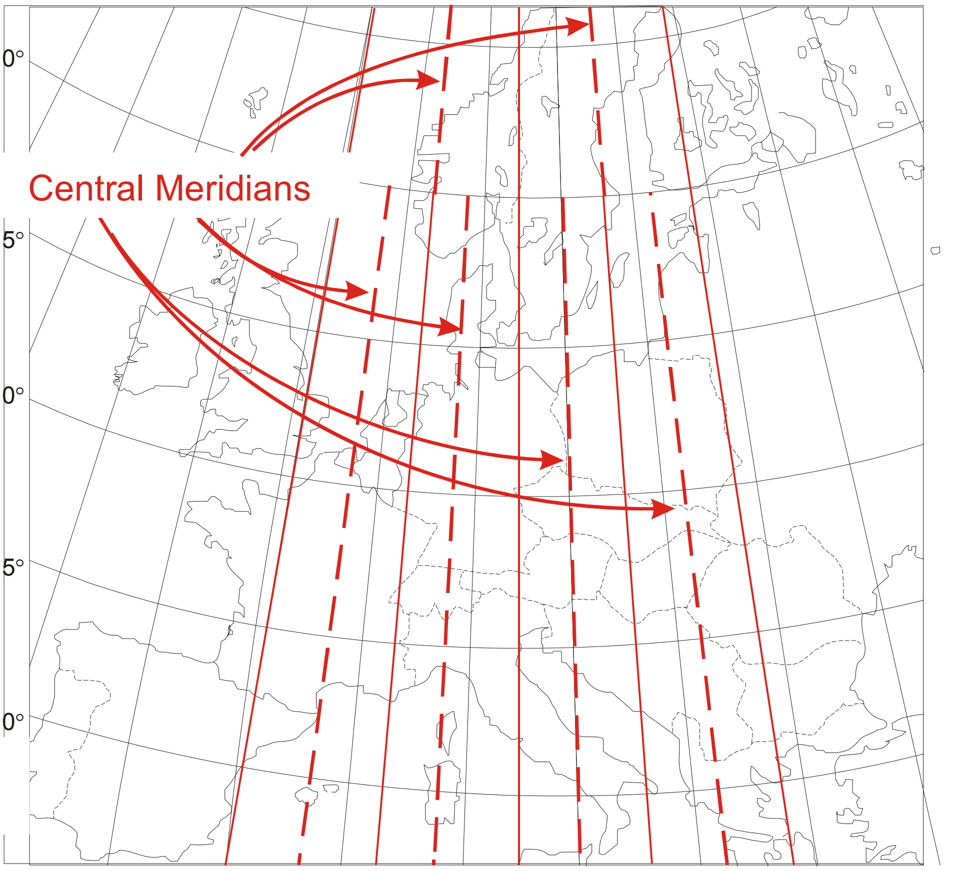
125. **Ordnance Survey Maps of UK**. Topographic maps of the British Isles are available at scales of 1:250,000 and 1:50,000 based on the Ordnance Survey (OS) maps. The scales are adjusted so that they are correct, not at the meridian of tangency (2° W), but at some distance on either side of it. The scale at 2° W is 0.9996 of the stated scale; at the east/west extremities of the map cover the scale is about 1.0004 of the stated scale. Had the scale been made correct at 2° W, then scale deviation of the order of 8 parts in 10,000 would have occurred at the east/west extremities; this mean scale device balances the overall scale deviation and hence halves its effective magnitude. The stated scale is correct along two lines parallel to the meridian of tangency, one 180 km east of it, the other 180 km west. The OS map projection is illustrated in Fig 41.

9-3 Fig 41 OS on Transverse Mercator Projection



126. **Joint Operations Graphics**. The 1:250,000 Joint Operations Graphic (JOG) is a series of topographical charts (Fig 42) which provide almost worldwide coverage of the land areas from latitude 80° S to latitude 84° N. Each sheet of the series covers 1° in latitude and between 1.5° to 8° in longitude (depending on latitude), and is constructed on its own individual transverse Mercator projection of the International Ellipsoid with meridian of tangency at the centre of the sheet. The scale deviation of the projected graticule of a sheet does not exceed 0.01%. Adjoining sheets fit exactly along north and south edges and although, in fact, they do not fit exactly along east and west edges the discrepancies are so small as to be unnoticeable. Charts of this series carry a reference grid, such as the British National Grid or one of the zones of the UTM Grid appropriate to the country or region covered. These reference grids may be based on different projections, ellipsoids or points of tangency but are designed so that the scale deviation is usually less than 0.15% within the grid area. Although, strictly, the projected graticule of a sheet and the projected grid are independent of each other, either may be used for positioning and navigation purposes.

9-3 Fig 42 Joint Operations Graphic (JOG) Projection System



127. **Summary of Properties**. The properties of the transverse Mercator are summarized below.

a. Scale is constant along the meridian of tangency, but expands (for a spherical Earth) with the secant of the false latitude.

b. Since the false meridians and parallels are projected by Mercator's method the projection is orthomorphic.

c. The meridian of tangency and all great circles at right angles to it (i.e. false meridians) are straight lines. All other great circles are curves concave to the meridian of tangency.

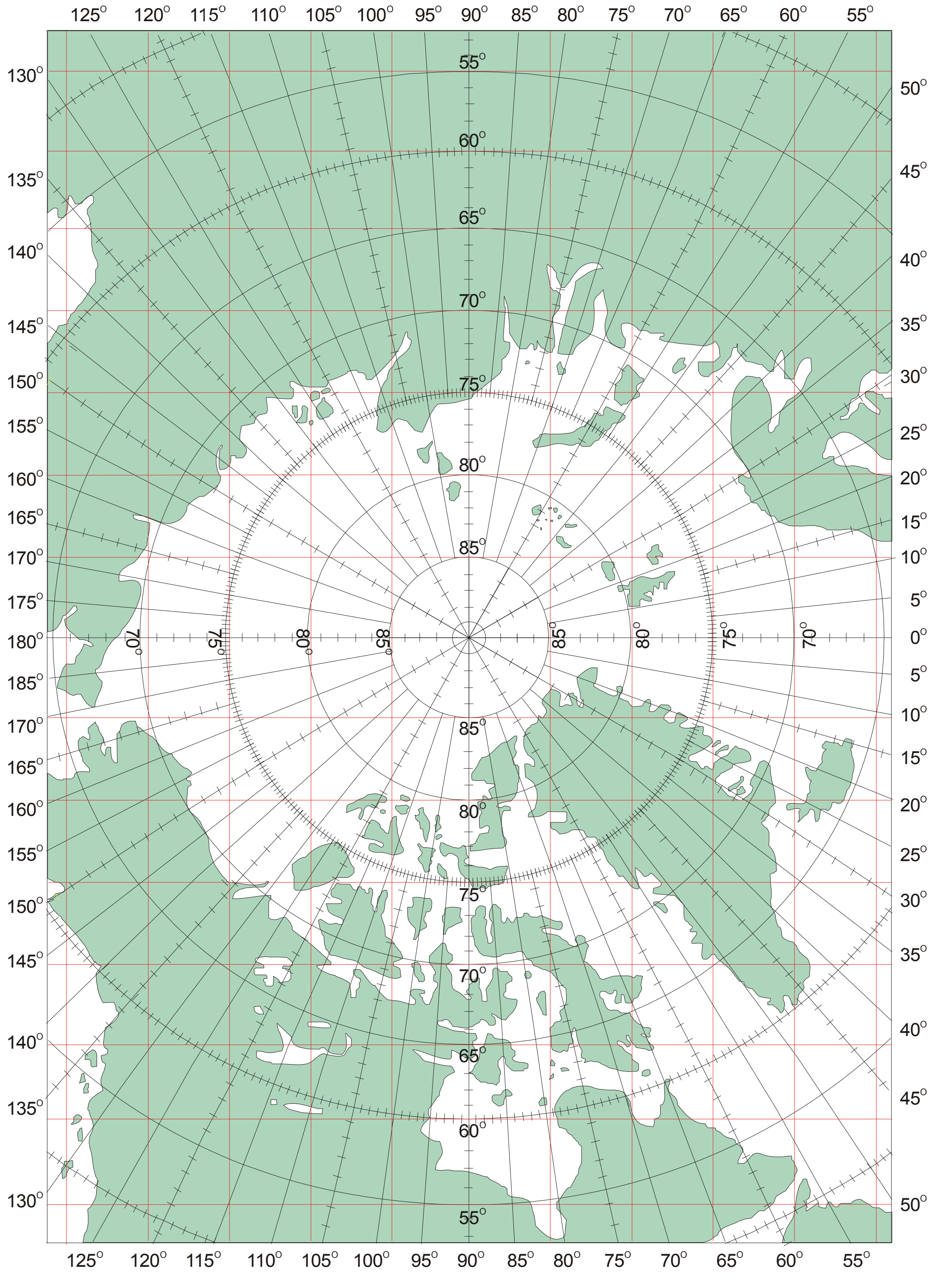
d. Rhumb lines are curves.

e. Near the meridian of tangency scale is almost constant (1% error 480 nm removed from it), great circles are almost straight lines, area distortion is minimal and the graticule appearance is regular. Charts do not, of course, fit along east and west edges if based on different meridians of tangency, but provided the separation of these meridians is small (as with the JOG) the discrepancy is not inconvenient.

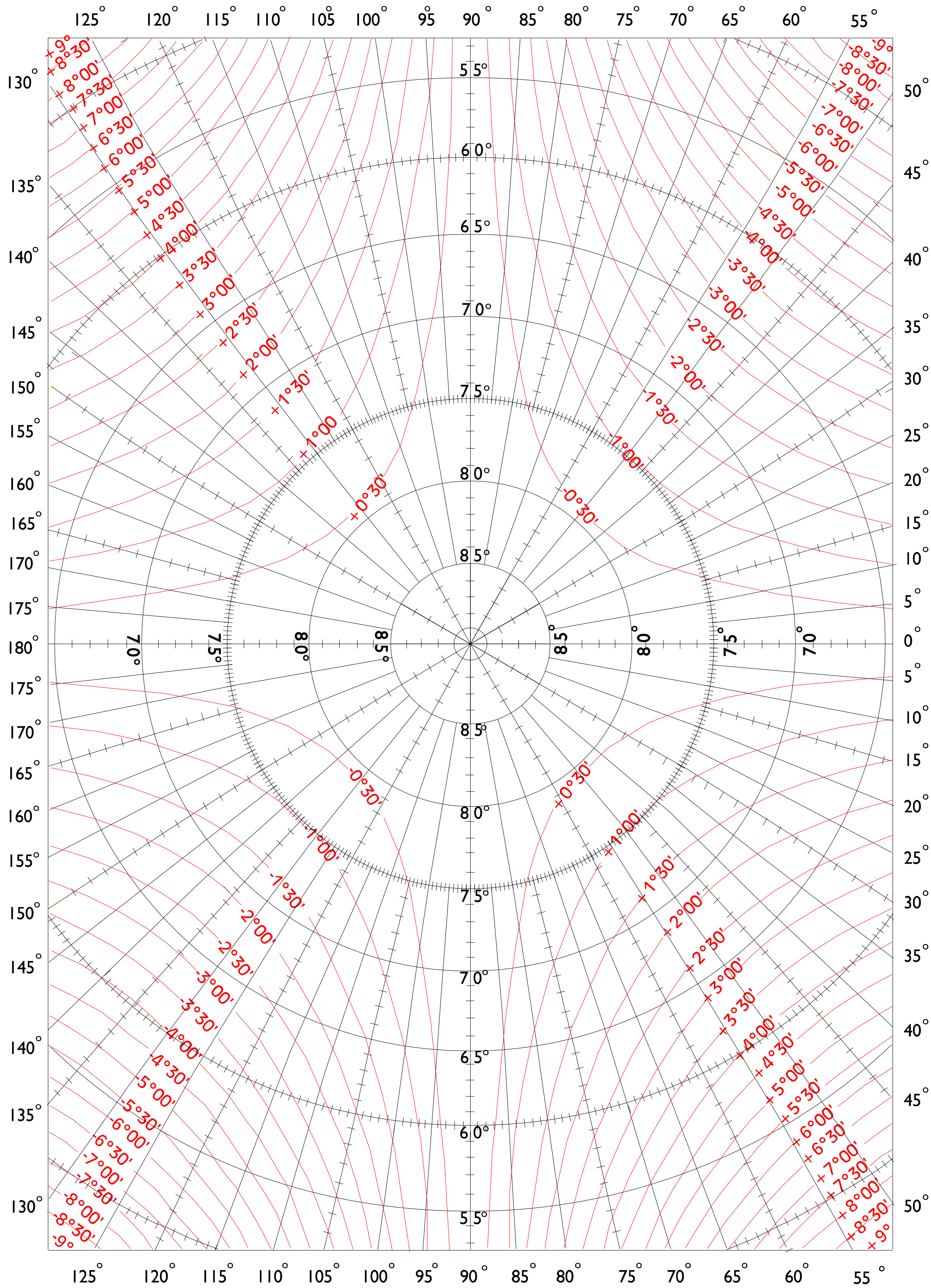
128. **Gridded Transverse Mercator Charts**. Transverse Mercator charts are often provided with an overprint of the false graticule, to be used with some form of grid navigation. By analogy with the normal Mercator, the grid is of approximately square appearance within about 500 nm of the great circle of tangency. Grid north is the direction of the false pole and a gyroscope device initially aligned with grid north will maintain this datum direction if suitable torquing terms are applied to it. A word of warning is necessary when convergence is considered. The geographical meridians are curved, even though on a small part of a chart they appear to be straight lines; hence the angle between true north and grid north is not constant along a given geographical meridian (as it is on a gridded conical chart). It is of importance,

for example, when converting true heading to grid heading for checking purposes, to apply convergence for the particular position: various tables have been drawn up for this purpose and values are printed on some charts. A gridded polar chart and a convergence correction chart are illustrated in Figs 43 and 44. When using gridded transverse Mercator charts it is possible, if false north can be accurately defined, to steer false rhumb line track; such a system is the same as navigation on a normal Mercator if false latitude and longitude are substituted for their geographical counterparts.

9-3 Fig 43 Grid on Polar Transverse Mercator



9-3 Fig 44 Convergence Correction Chart



CONICAL PROJECTIONS

Introduction

129. The cylindrical projection is best suited to the representation of a single great circle (such as the equator) and the band of the Earth's surface close to it, while the azimuthal projections depict very well the area surrounding a point. The conic projections fill the gap by best projecting small circles and the bands of surface close to them.

130. From a navigation point of view, the conformal conics are the most important members of the group, and most of this chapter is devoted to them. However, some discussion of perspective conics may be found helpful.

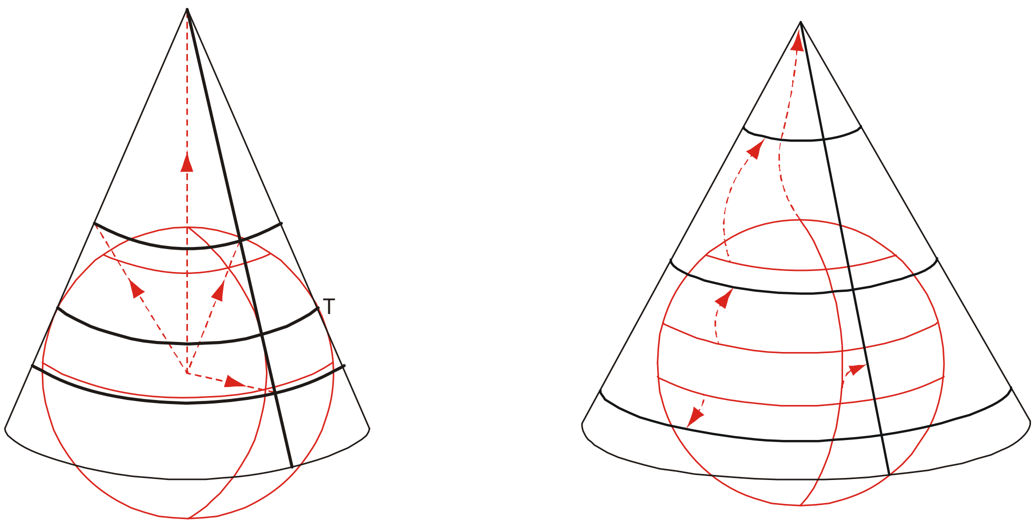
General Description

131. All the conic projections described in detail are normal to the equatorial plane; oblique conics are sometimes drawn but they are not often found to be useful in navigation. The simplest arrangement is that of a cone, tangent at a parallel of latitude (Fig 44a), onto which the meridians and parallels are projected.

132. The projection can be perspective or non-perspective. In the perspective case, the graticule is a linear projection, usually from the centre of the sphere, as in Fig 45a. In the more general non-perspective case, the graticule is positioned mathematically on a cone which may touch, or cut through, the sphere as shown in Fig 45b.

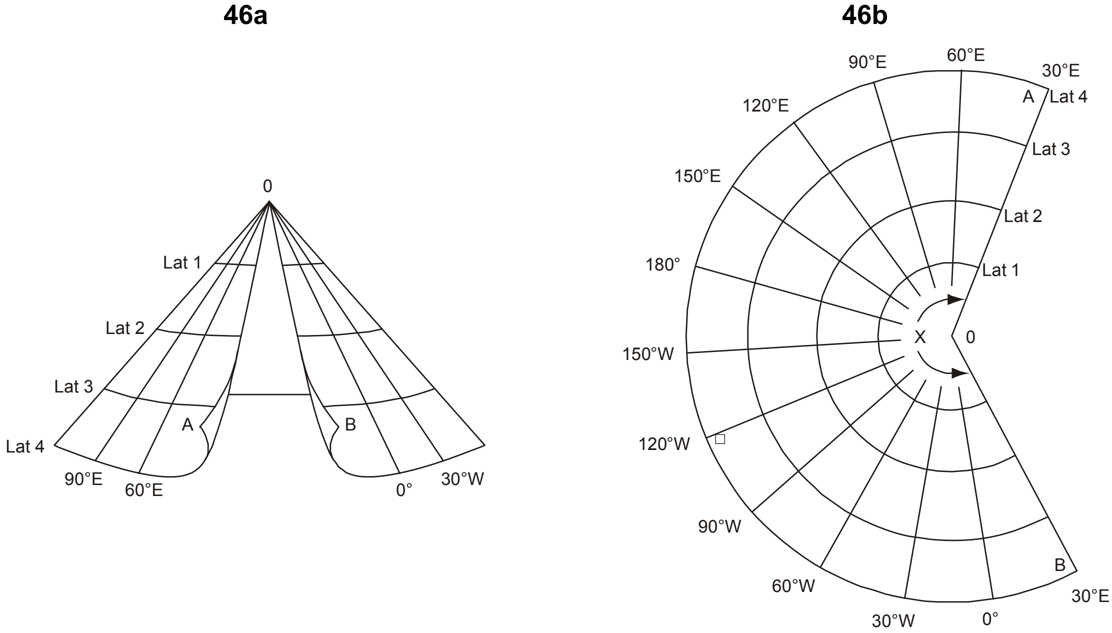
9-3 Fig 45 Conical Projections

45a – Perspective Projection | **45b – Non-perspective (Lambert's) Projection**



133. **Appearance of Graticule**. After projection, the cone is cut and unrolled (Fig 46a). This is known as the development of the cone. The meridians appear as straight lines radiating from a point, which, in all normal projections, represents the geographic pole. The parallels of latitude are arcs of circles, concentric at this point. The developed cone is illustrated in Fig 46b.

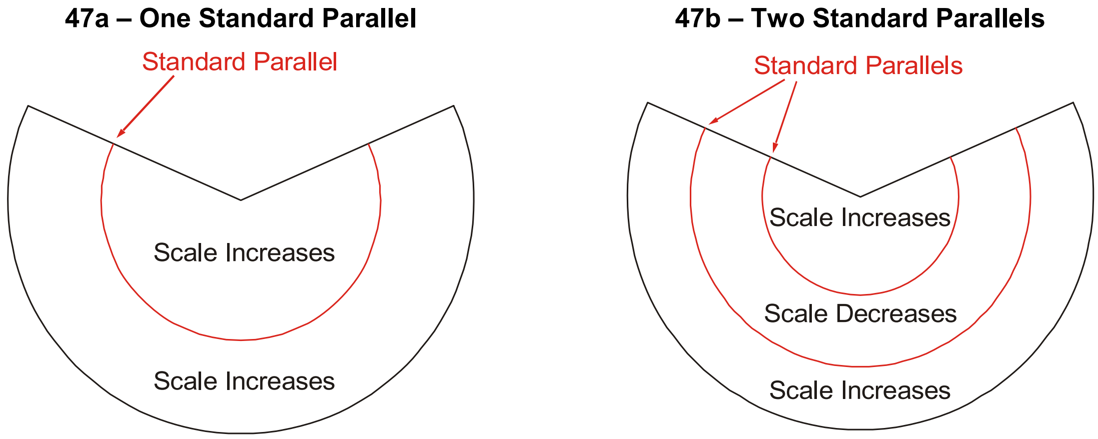
9-3 Fig 46 Development of the Cone



134. **Standard Parallels**. A 'standard' parallel of latitude is one which is projected at reduced Earth scale. It is possible to have more than one standard parallel and one- and two-standard parallel projections are discussed. On a one-standard parallel projection, the standard parallel is also the parallel of origin (λ_0).

135. **Scale Expansion**. On all the conformal conics, and on all the perspective conics, the pattern of scale change is that shown in Fig 47. Scale is correct along the standard parallels and increases away from them; in the two-standard case it decreases between them.

9-3 Fig 47 Conformal Conic Scale



Constant of the Cone

136. When the cone is developed, the reflex angle at the centre of the sector (x in Fig 46b) represents 360° of longitude. The ratio of x° to 360° is known as the 'constant of the cone' (or the convergence factor) and is denoted by n. Its value is normally printed on a conic projection, and chart convergence can be obtained from the formula:

$$n \times \text{ch long}$$

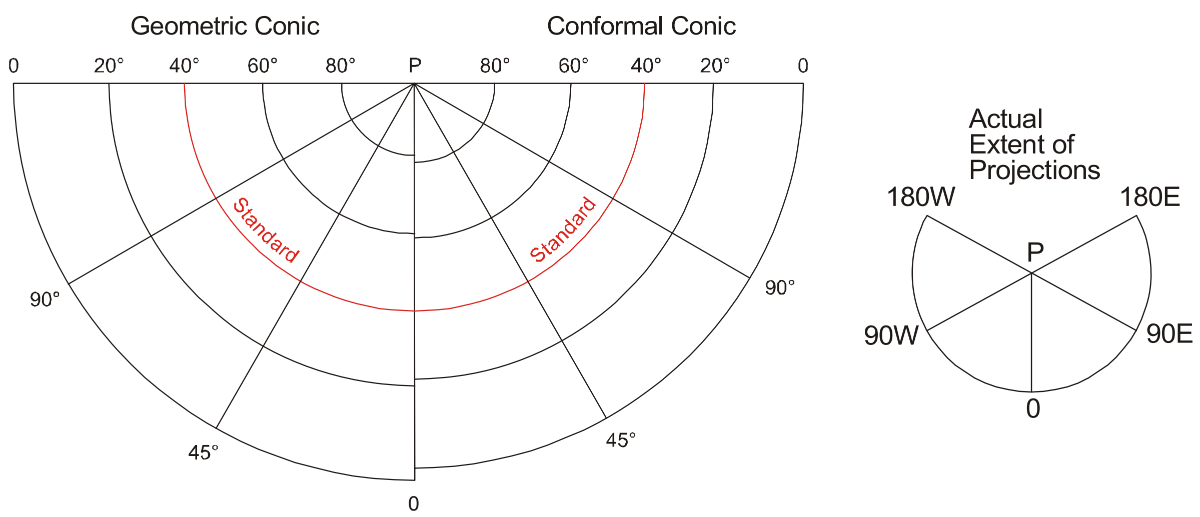
CONFORMAL CONIC PROJECTIONS

Conformal One-Standard Conic Projection

137. A geometric conic is a perspective projection onto a cone at a parallel of latitude, which is the standard parallel for a one-standard conic projection. The point of projection is the centre of the Earth. The conformal version of the one-standard conic is derived from the geometric conic by adjusting the radii of the parallels to make the scale at any point the same in all directions. The standard parallel and the parallel of origin (λ_0) are also coincident on this projection.

138. The projection is non-perspective on to a cone tangent at the latitude chosen as the standard parallel. The meridians are drawn exactly as in the geometric case, but the parallels (see Fig 48) are moved slightly nearer the standard parallel. The pole remains at the apex of the cone and represents the oddity of the projection, for it is not conformal at that point. This is evident from the angle between two meridians; at the pole this angle should be ch long but on the chart it is n × ch long (the projection is everywhere else conformal, even at latitude 89º 59'). Scale factor is 1 on the standard parallel and increases with distance from the standard parallel.

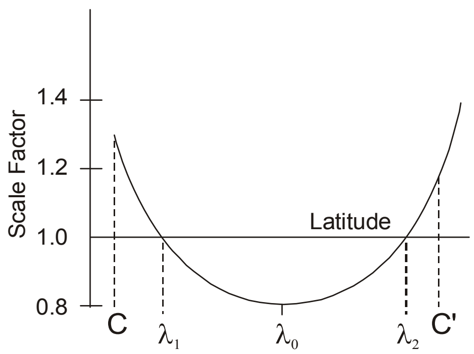
9-3 Fig 48 One Standard Conformal Conic



Lambert Conformal Conic Projection

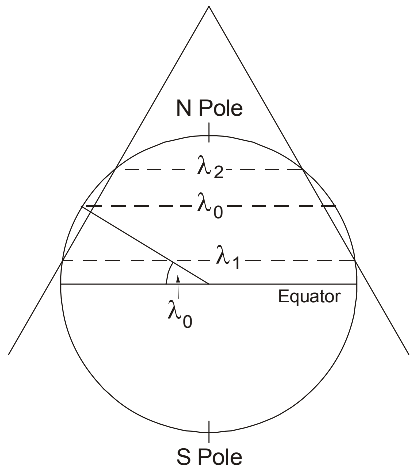
139. The Lambert conformal is a non-perspective projection with two standard parallels. It is obtained by simply declaring the scale to be correct (i.e. equal to reduced Earth scale) along two parallels which are approximately equally spaced about λ_0. The scale factor at these standard parallels is 1, varying at other latitudes, as illustrated in Fig 49.

9-3 Fig 49 Lambert Conformal Scale Factor



140. **Description**. The projection can be regarded as the projection of a slightly larger reduced Earth onto the original cone, which is so placed as to cut it at two parallels, λ_1 and λ_2, as in Fig 50. The meridians are straight lines radiating from the pole and inclined to each other at n × ch long, where n is sin λ_0. For all practical purposes, λ_0 is the mean of the two standard parallels, λ_1 and λ_2, and is, of course, the latitude of minimum scale factor.

9-3 Fig 50 Approximate Projection Description



141. **Advantage of Two Standard Parallels**. The advantage of a projection with two standard parallels is to give an increase of the area of the Earth within which the scale deviation of the projection will not exceed a given amount, i.e. in the example at Fig 49, if a straight edge calibrated to the scale at λ_1 or λ_2 is used, the error is within 20% at λ_0, C and C′. Thus, by choosing a scale factor at λ_0 for the Lambert projection, all other scale factors can be determined. The scale factor at λ_0 is sometimes called the scale reduction factor (SRF).

142. **Standard Parallel Separation**. The shape of the scale factor graph fixes a relationship between SRF and the distance apart of the standard parallels. The choice of one determines the other. The actual connection depends upon latitude, but over a wide range (up to about 80º N), Table 2 below is a useful guide.

Table 2 Relationship between Standard Parallel Separation and Scale Reduction Factor

Scale Reduction Factor	Scale Deviation at λ_0	Standard Parallel Separation
0.99	1%	16°
0.98	2%	23°
0.97	3%	28°
0.96	4%	32°

143. **Minimizing Scale Deviation on the Chart**. Scale factor increases away from λ_0 in both directions, passing through 1 at the standards, λ_1 and λ_2. If the standard parallels are placed so as to divide the latitude coverage of a chart in the ratio 1:4:1 or 1/6:4/6:1/6, then the best balance of scale deviation is achieved. This is known as the 1/6 rule. Furthermore, if a maximum standard parallel spacing of 14º is observed, then the scale deviation will be limited to <1%. Thus, a Lambert chart can be considered as 'constant scale' if both:

a. The spacing of the standard parallels does not exceed 14º Ch Lat, and

b. The 1/6 rule is observed.

144. **Great Circles**. Near λ_0, great circles are approximately straight lines; away from λ_0 they are curves concave to λ_0. The angle (Δ) between the great circle and the straight line is given by:

$$\Delta = \tfrac{1}{2} \text{ ch long (sin mean lat} - \text{n)}$$

Near λ_0, the great circle is very well represented by a straight line and, on most parts of actual charts, the divergence between the two is not noticeable.

145. **Distance Measurement**. When measuring distances on Lambert projections, the mid-latitude scale in the area should be used, but over long tracks, which pass from areas of negative scale error to positive scale error, a straight edge graduated at the stated scale can be used. The amount of care which is required can be assessed from para 142. If the standards are within 16° of each other, then a straight edge can be used everywhere within about 12° of λ_0. If the separation is greater than 16°, then a constant-scale straight edge should only be used when measuring long distances or if the flight is within the band of 1% scale deviation about a standard parallel.

146. **Summary of Properties**. The properties of the Lambert Conformal projection are as follows:

a. The projection is conformal with two standard parallels (where scale factor is 1).

b. Scale factor is at a minimum at the latitude whose sine is n. This latitude is about the mean of the standards.

c. Scale factor change is roughly of the form of the secant of the ch lat from λ_0.

d. The projection is not conformal at the poles and scale factor is very large near the poles.

e. Great circles are curves concave to λ_0. Near λ_0 they are approximately straight lines.

f. Sheets will join only if they are based on the same standard parallels and are at the same scale.

147. **Uses**. Lambert's Conformal charts are in widespread use except for polar latitudes. Examples of current charts are: 1:500,000 Global Navigation Charts (GNC), 1:2,000,000 Jet Navigation Charts (JNC), 1:500,000 Tactical Pilotage Charts (TPC), 1:100,000 Operational Navigation Charts (ONC) and 1:500,000 Low Flying Charts (LFC). The moving map filmstrip used in the Tornado is based on Lambert's charts but modified to a form of equidistant cylindrical projection (Plate Carree) during photography.

NAVIGATION PROJECTIONS - COMPARISON AND SUMMARY

Introduction

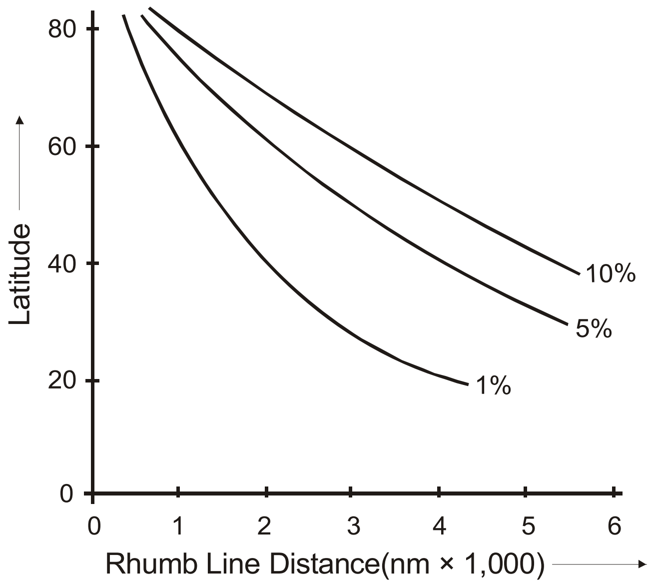
148. In this chapter, the navigation projections are compared and their properties are summarized.

Great Circles and Straight Lines

149. In general, conformal projections do not portray great circles as straight lines, except the equator and meridians in some cases. It is therefore necessary to provide some guidelines as to when it is worthwhile to plot the great circle rather than the straight line.

150. **Distance**. From a distance-saving point of view, there is usually little to gain in flying true great circle routes on the stereographic projection or on Lambert's projection. The difference between the straight line and the great circle distance for flights of less than 2,000 nm contained within ±25° of the parallel of origin (λ_0) is less than 0.5 % of the distance. Navigation charts based on these projections are usually confined to a much smaller latitude spread, but since this is not the case with the Mercator projection, special care is needed with it. Fig 51 illustrates the penalty, expressed as percentages of great circle distances, in flying east-west rhumb line tracks at various latitudes.

9-3 Fig 51 Mercator Projection Distance Penalty

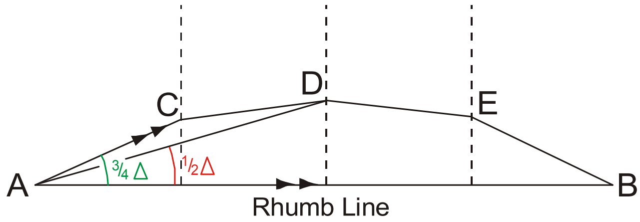


151. **Direction**. The angle between the great circle direction and the straight line is given by:

$$\Delta = ½ \text{ ch long (sin mean lat} - n)$$

approximately on Mercator's and on Lambert's projection, and exactly on the stereographic projection. Use can be made of Δ to sketch in a series of straight lines which will correspond very well with the great circle in most cases. The straight-line distance, AB in Fig 52, is measured in some constant unit and perpendiculars are erected at the quarter, half and three-quarter length points. The line segments AC, CD, DE, EB are then drawn using angles 0.75Δ and 0.5Δ, and 0.25Δ as shown in the diagram to obtain the intercepts C, D and E. The direction is concave to λ_0.

9-3 Fig 52 Approximate Great Circle

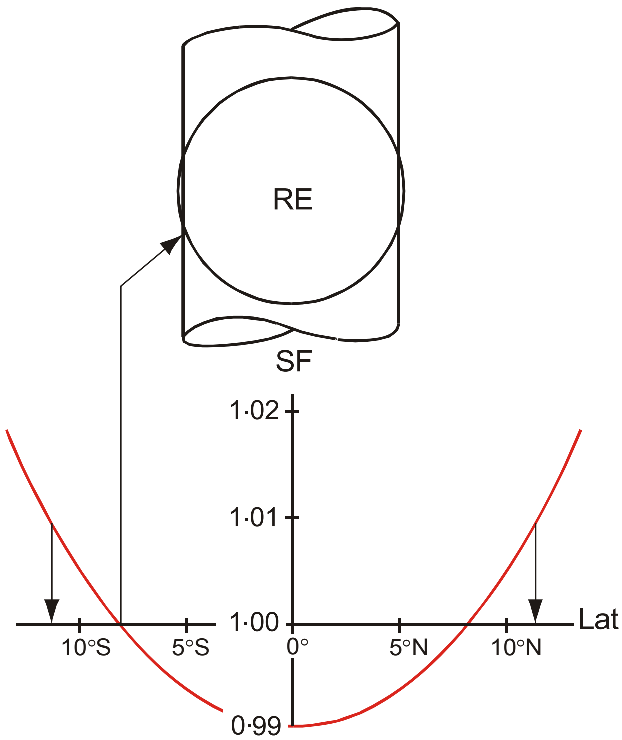


Scale Reduction Factor

152. Scale reduction factor (SRF) was used to develop the Lambert conformal projection from the one-standard conformal conic. It is also the device used in the Ordnance Survey transverse Mercator projection of the United Kingdom to reduce scale deviation. SRF can be used for any conformal projection to produce the same effect.

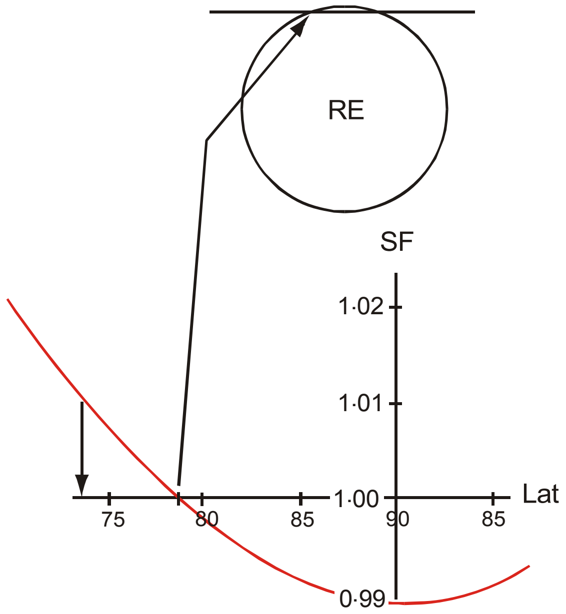
153. If, for example, the scale factor everywhere on a Mercator projection is multiplied by 0.99, two parallels, one at about 8° N and the other at about 8° S, will gain scale factors of 1. The projection will be of the form illustrated in Fig 53, on to a cylinder cutting a larger reduced Earth in these two parallels, and reduced Earth scale can now be used everywhere between about 11.5° N and 11.5° S with a deviation of less than 1%, i.e. with almost constant scale.

9-3 Fig 53 Mercator with Two Standard Parallels



154. The idea can be applied to the polar stereographic. A scale deviation of 1% occurs at about 11.5º from the pole. To enlarge the area of almost constant scale it is necessary to multiply all scales by 0.99. Scale factor becomes 0.99 at the pole and 1 at about latitude 78.5º. Constant scale measurement can be used up to 16º (latitude 74º) from the pole where scale factor is now 1.01. This projection can now be thought of as stereographic on to a plane cutting the Earth at latitude 78.5º (Fig 54).

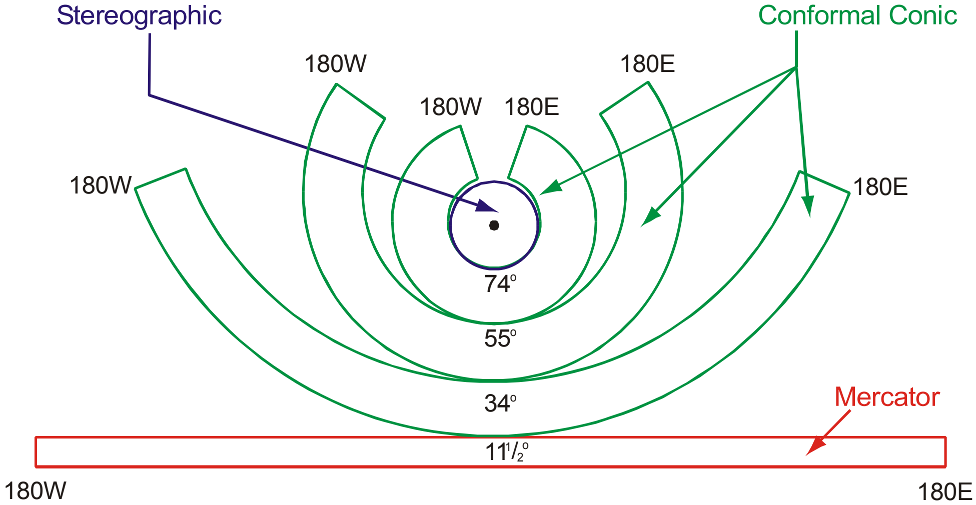
9-3 Fig 54 Modified Stereographic



155. Using the Lambert conformal projection, a scale deviation of 1% can be achieved by placing the standard parallels some 16º apart; an area bounded by parallels approximately 3º or 4º beyond these then has the required maximum scale deviation.

165. The use of scale reduction factor allows conformal mapping of a hemisphere on to five projections with scale deviation everywhere less than 1%. The projections are a Mercator at the equator, a polar stereographic and three Lambert conformal conics covering latitude bands shown in Fig 55.

9-3 Fig 55 Conformal Mapping of a Hemisphere



Errors in Distance Measurement

157. On the majority of Lambert conformal charts available for navigation no sensible error is introduced through using the constant scale for distance measurement, but care is needed on any chart on which the standards are about 16º or more apart. This care is especially necessary when the area of operation is at the centre or at the extremes of the projection.

158. Similarly, no appreciable error will result from using reduced Earth scale in equatorial regions on a Mercator projection, or near the pole on a polar stereographic projection. When there is any doubt, on any projection, the track should be divided into latitude bands of 100 nm to 200 nm and the mean latitude scale at each band used.

PROJECTION SUMMARY

Choice of Chart

159. Choosing the best chart for a particular task may appear at first sight a difficult task, but it is often reduced simply to a choice between only two or three charts and the decision may finally be made by availability. The following summary suggests suitable charts for a number of purposes.

Planning Charts

160. Planning charts are used for display and for route and operational planning. They must, in general, cover large areas with minimal distortion, or have some particular useful property, such as showing great circles as straight lines, or radii of action at constant scale. The scales used for planning charts are necessarily small, in the order of 1:10,000,000 to 1:20,000,000.

161. Without doubt, the best general-purpose display and planning projection is the stereographic. It is conformal, it has the smallest scale expansion, it can display almost the whole world on one sheet, and great circles can be drawn with a minimum of difficulty since they are lesser arcs of circles.

162. For smaller areas the Lambert conformal in middle latitudes, and the Mercator in low latitudes, provide the best working projections.

163. **Summary**. The applicability of the various projections to planning tasks may be summarized as follows:

Task		Projection Most Suited
Large Area	-	Stereographic
Small Area		
Middle	-	Lambert Conformal
Low Latitudes	-	Mercator
Polar Regions	-	Stereographic
Radii of Action	-	Azimuthal Equidistant
Great Circles	-	Gnomonic

Plotting Charts (General)

164. Plotting charts must be conformal. They should also be easy to use, which implies that the scale for distance measurement should be uncomplicated and that the measurement of headings and bearings should be made from a straight-line datum. The simplest form of navigation is constant heading and for this the direction datum should be parallel over the whole chart.

165. If the direction datum is True North, then the Mercator projection fulfils this requirement, but it cannot be used in high latitudes and is not the best projection in medium latitudes since the rhumb line is excessively longer than the great circle. The plotting of chords of the great circle from a gnomonic satisfies the distance difficulty, but it also defeats the object by introducing many changes of direction.

166. The best all-round solution in middle latitudes is the Lambert conformal projection, on which scale is almost constant. A grid can be overprinted, and the corrections to magnetic or other datum direction to indicate grid north are no more difficult to apply than those to obtain True North. In polar regions, the Polar Stereographic is the best chart.

167. **Summary**. The usefulness of the projections for plotting purposes is shown below:

12º S to 12º N	-	Mercator
12º to 74º	-	Lambert Conformal
74º to 90º	-	Polar Stereographic or Transverse Mercator

Plotting Charts (Special)

168. Special plotting charts are available when the area of operation is specified by a great circle and a narrow band around it.

169. If the area of operation extends from polar to equatorial regions the best single projection is the transverse Mercator.

170. If the area is along an inter-cardinal great circle then the oblique Mercator projection provides the best solution. Such strip maps are produced for important high-density routes.

171. **Summary**. The best charts for special plotting uses may be summarized as:

Large ch lat, small ch long	-	Transverse Mercator
Inter-cardinal Great Circle	-	Oblique Mercator

Topographical Charts

172. Topographical charts for navigation must be conformal and have the same properties as other plotting charts. Thus, the Mercator and Lambert projections are usually chosen.

173. However, an additional problem is introduced when large-scale topographical charts of world-wide coverage are considered. Such charts, which are intended primarily for joint air/ground operations, must have very small scale errors and adjoining sheets must fit north/south and east/west as exactly as possible. These requirements are best met by a sequence of transverse Mercator projections based on close meridians.

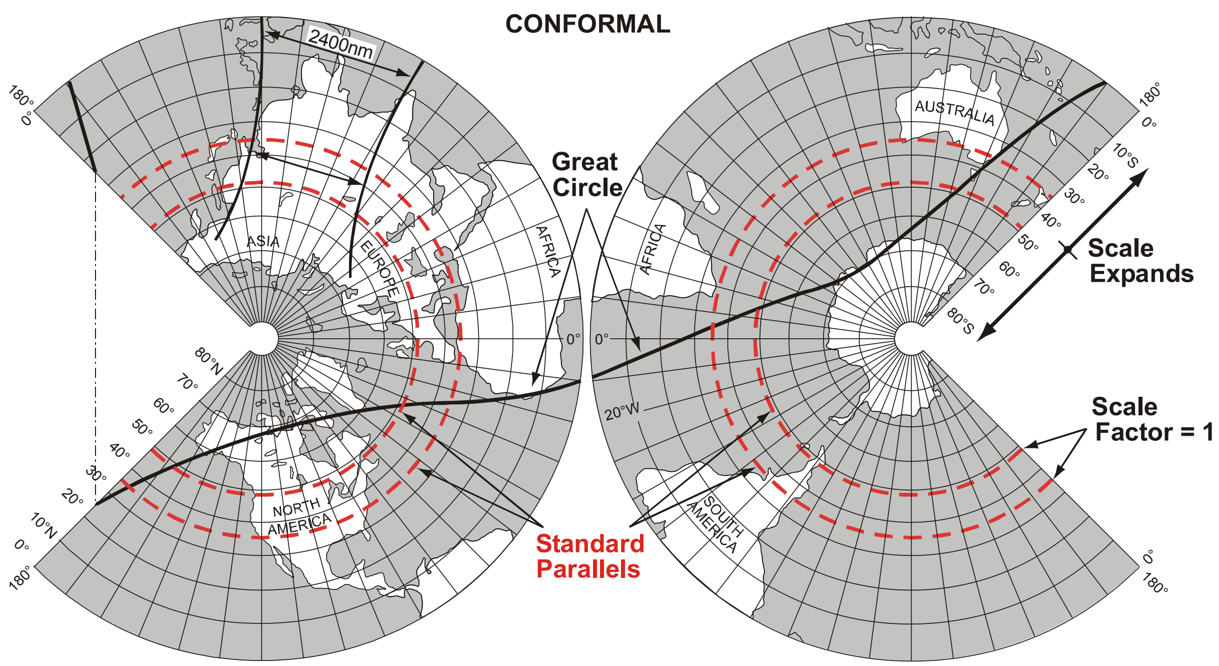
174. **Summary**. The appropriate projections for topographical use are summarized as follows:

General	-	Lambert Conformal
	-	Mercator (Low Latitudes)
World-wide (Large Scale)	-	Transverse Mercator

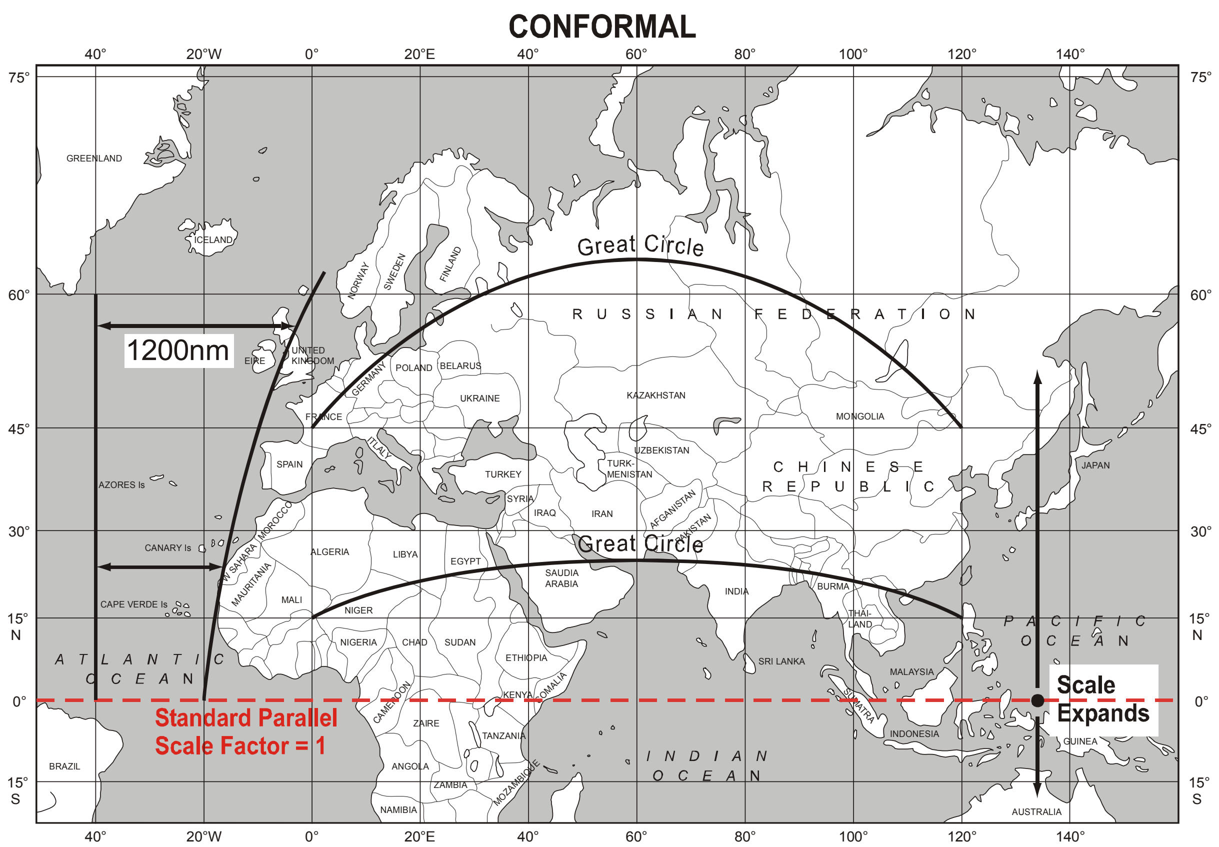
The Navigation Projections

175. The projections of importance in navigation are summarized in Figs 56 to 62.

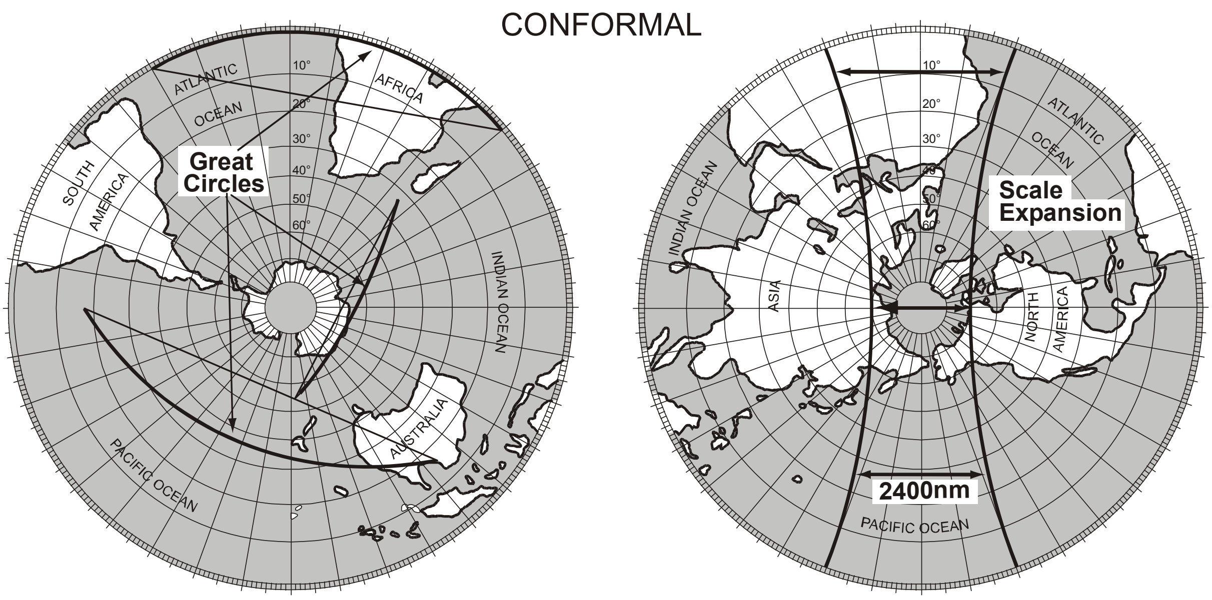
9-3 Fig 56 Lambert Conformal Projection



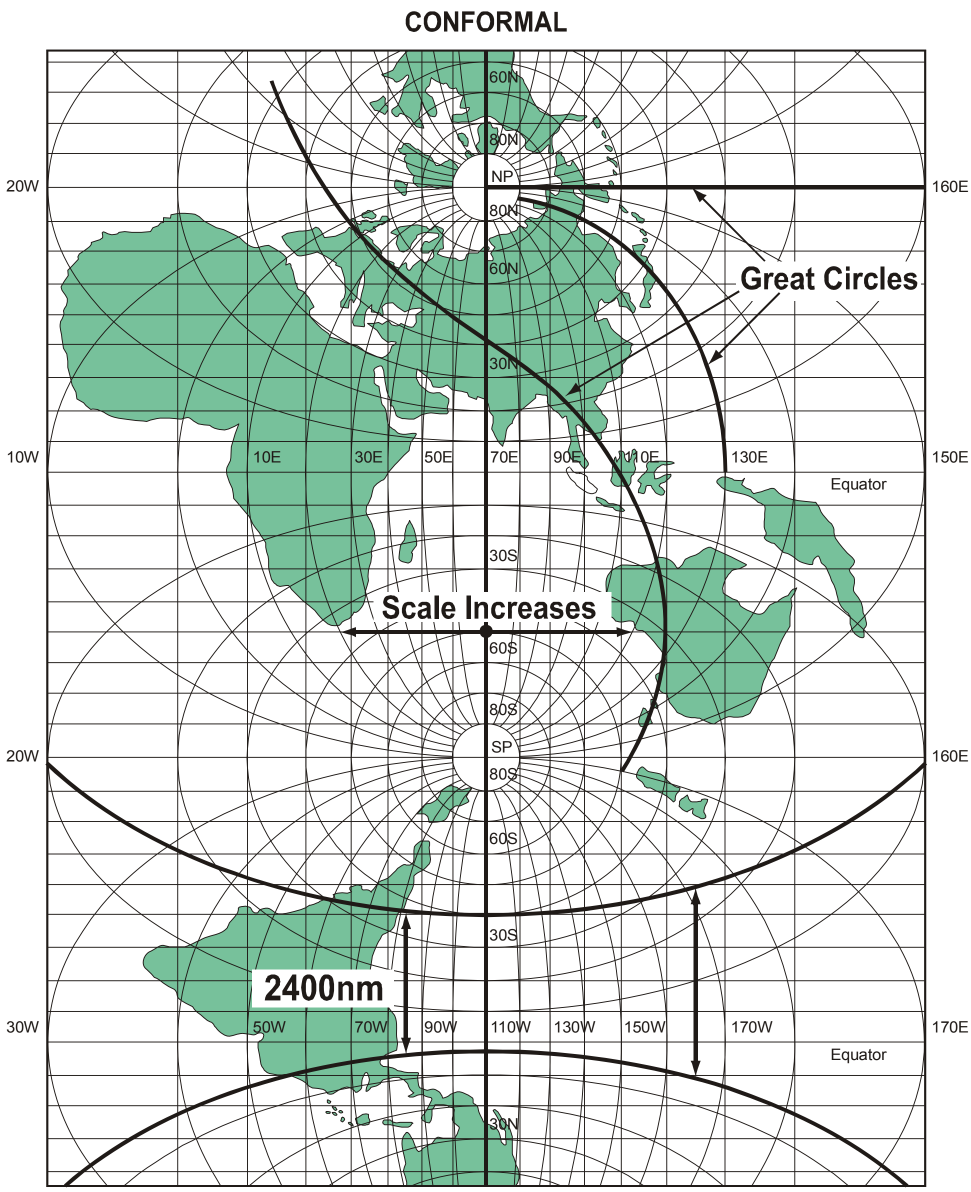
9-3 Fig 57 Mercator Projection



9-3 Fig 58 Polar Sterographic Projection

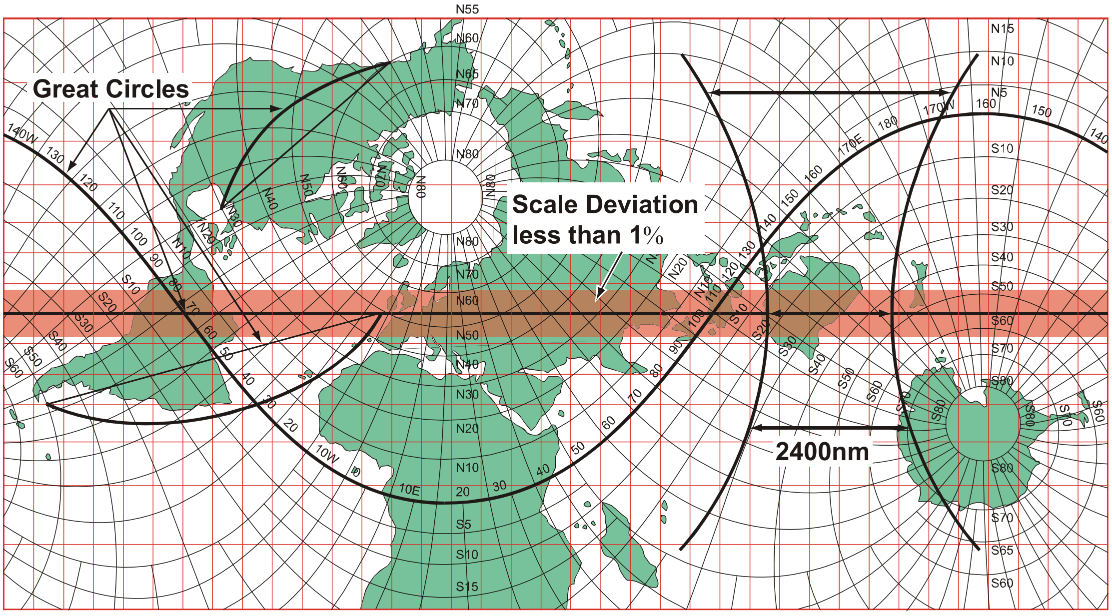


9-3 Fig 59 Transverse Mercator Projection



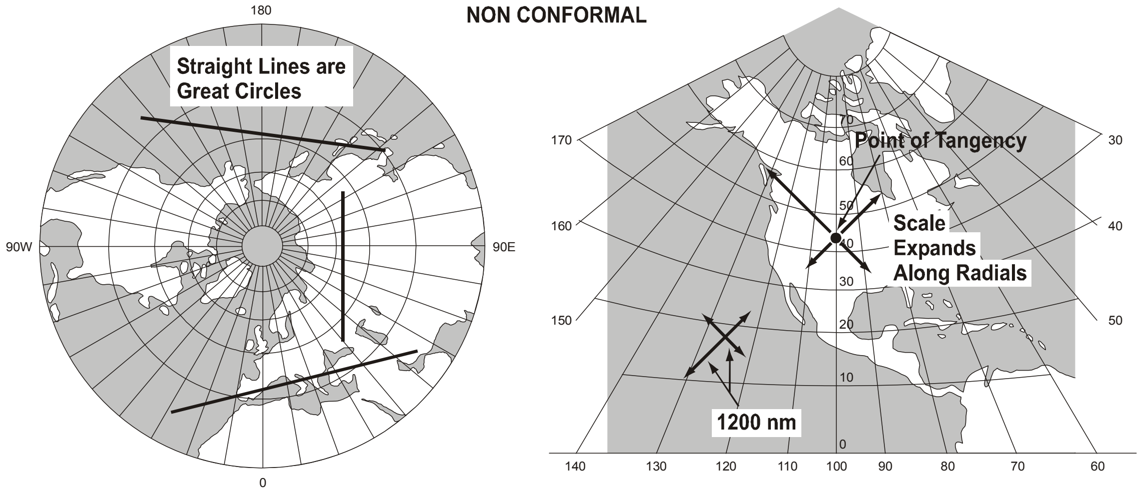
9-3 Fig 60 Oblique Mercator Projection

CONFORMAL



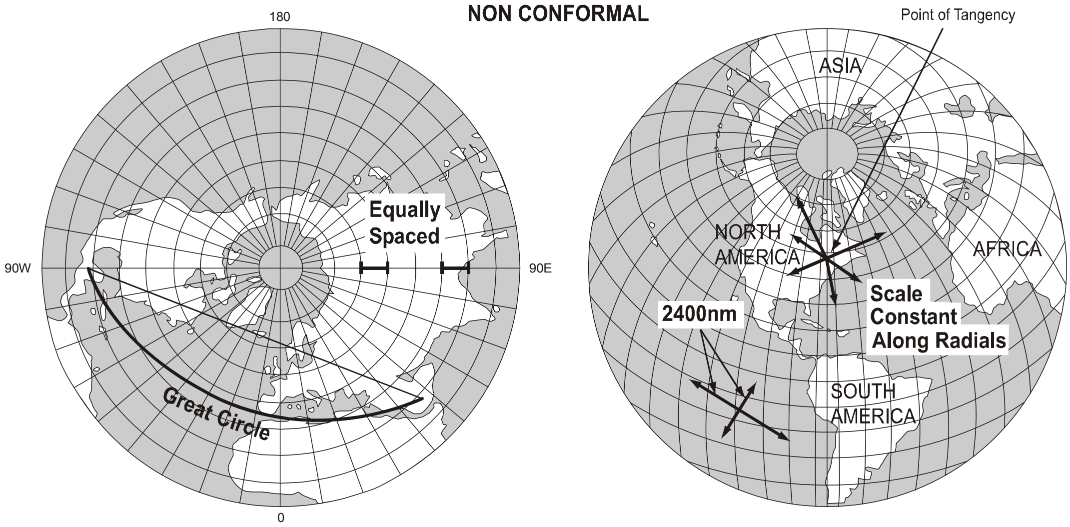
9-3 Fig 61 Gnomonic Projection

NON CONFORMAL



9-3 Fig 62 Azimuthal Equidistant Projection

NON CONFORMAL



CHAPTER 4 - THE TRIANGLE OF VELOCITIES - APPLICATION TO NAVIGATION

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Table of Figures

Speed and Velocity

1. It is important to realize the difference between the meanings of the words 'speed' and 'velocity'. Speed describes only the rate at which an object is moving. The statement that an aircraft has a speed of 400 kt gives no indication of the direction in which the aircraft is travelling, and this direction may be changed without any alteration of speed. Speed is thus a scalar quantity; it has magnitude but no direction.

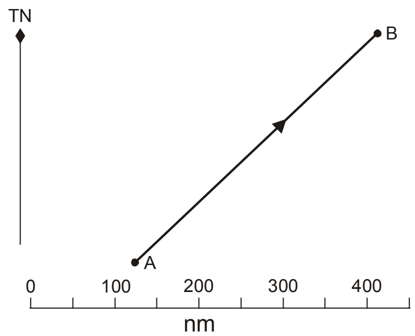
2. Velocity describes speed in a specified direction, it is said to be a vector quantity for it has both magnitude and direction. Thus an aircraft flying at 400 kt on a heading of 045° (T) has a different velocity from that of an aircraft flying at 400 kt on 090° (T), although their speeds are identical.

Vectors

3. Since a velocity is a speed in a given direction, it may be represented graphically by a straight line whose length is proportional to speed, and whose direction is measured from an arbitrary datum line. Such a straight line is called a vector.

4. The scale used in drawing vectors may be any that is convenient. The datum line for measurement of direction is, by convention, True North, and usually points to the top of the sheet. To indicate the direction and scale of the vector, it is usual to insert the True North symbol at some point in the diagram, and to indicate scale by a graduated scale line. Fig 1 illustrates the vector for an aircraft flying at 400 kt on a heading of 045° (T); the arrowhead indicates the sense of the vector, showing that the direction is 045° and not 225°.

9-4 Fig 1 A Vector



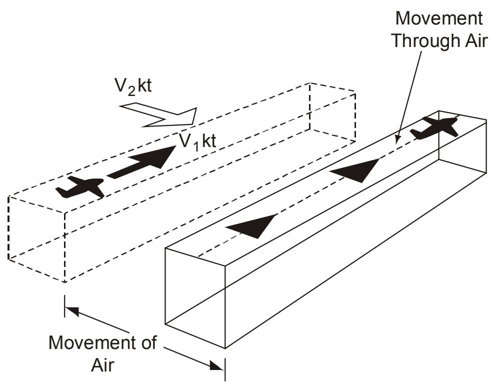
5. The discussion, so far, has concerned an aircraft's velocity relative to the air through which it moves. However, there is another factor which plays an important part in air navigation - the movement of the air itself.

6. **Wind Velocity**. Wind is air in natural motion, approximately horizontal. The direction and speed of that motion defines wind velocity (w/v), and it too can be represented by a vector. It is expressed as a five or six figure group; the first three figures refer to wind direction (the true direction from which it blows); the last two or three figures indicate wind speed in knots. The figures representing direction are separated from those of speed by an oblique stroke. Thus, a wind velocity of speed 45 knots blowing from the east would be written as 090/45, and one of 145 knots from the same direction as 090/145.

Vector Addition

7. Fig 2 illustrates the basic navigation problem; the aircraft is moving at V_1 kt through an air mass which itself is moving at V_2 kt (w/v). It is necessary to find the resultant of these two component velocities to determine the aircraft's path over the ground. To view an animation of Fig 2, click here.

9-4 Fig 2 Factors Affecting the Path of an Aircraft

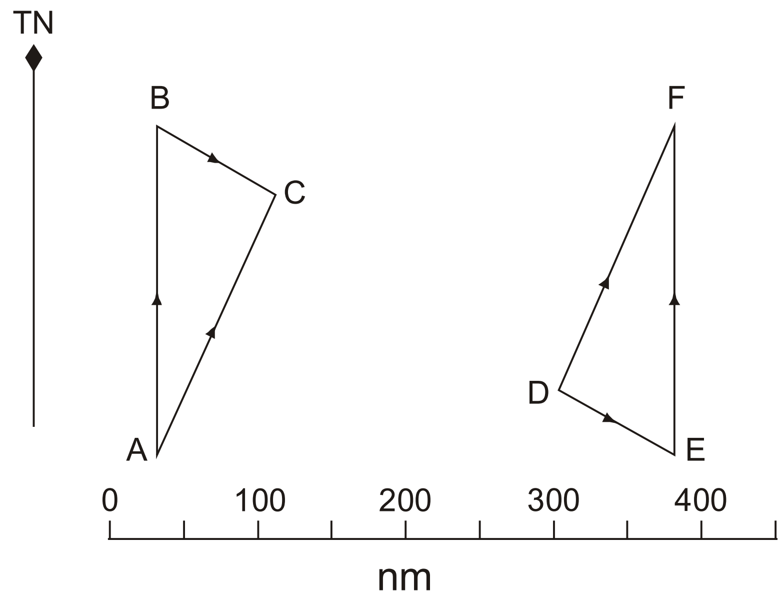


8. If the component velocities act in the same direction (i.e., the aircraft flies directly upwind or downwind), the resultant velocity is the algebraic sum of the aircraft speed and wind speed, along the aircraft heading. However, when the component velocities do not act in the same line, the resultant velocity is an intermediate speed in an intermediate direction. In such cases, it is possible to find the resultant by constructing a vector diagram, or triangle of velocities.

Triangle of Velocities

9. If the vectors (see Fig 3) of the aircraft's velocity (AB or EF) and wind velocity (BC or DE) are drawn (using the same scale), such that their sense arrows follow each other, then the resultant velocity vector is the third side. The sense of this vector is such that its arrow opposes the arrows of the component velocities around the triangle. Thus, in Fig 3, the vector of the resultant velocity is AC or DF.

9-4 Fig 3 Triangle of Velocities



10. It can be seen that AC and DF are identical in magnitude and direction; it does not matter in which order the initial component vectors are drawn as long as their sense arrows follow each other.

NAVIGATION COMPONENTS OF THE TRIANGLE OF VELOCITIES

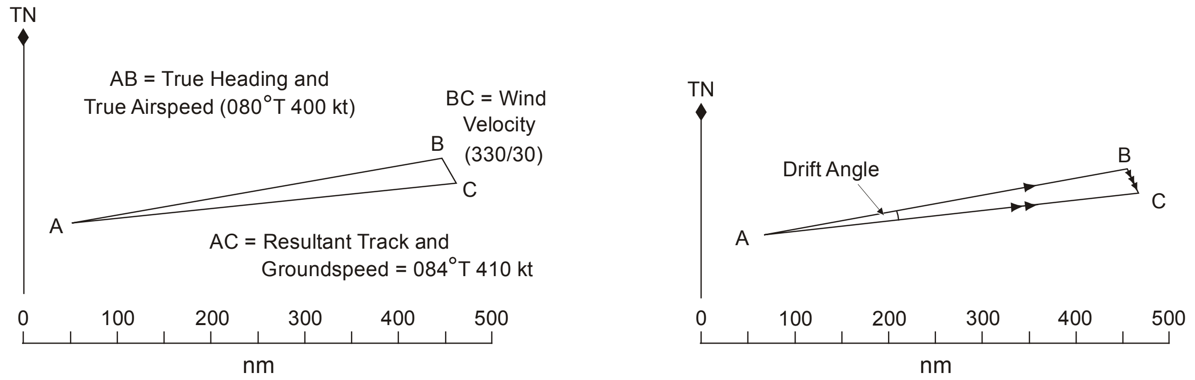
General

11. Using the triangle of velocities to solve the basic navigation problem, the component vectors represent the aircraft's velocity (true heading and true airspeed) and wind velocity; the resultant vector represents the aircraft's true track and groundspeed (see Fig 4a).

12. In addition to these vectors, the other important quantity in navigation is the angle between the aircraft's velocity vector and the resultant; this is the drift angle (see Fig 4b).

9-4 Fig 4 Navigation Vectors

a Component Parts of the Triangle of Velocities **b Arrow Convention**



13. **Arrow Convention**. The vectors are not normally labelled as in Fig 4a, but are identified merely by the number of arrows on the vector. The convention, illustrated in Fig 4b, is:

a. The true heading and true airspeed vector carries one arrow, pointing in the direction of heading.

b. The track and groundspeed vector carries two arrows, pointing in the direction of track.

c. The wind velocity vector carries three arrows pointing in the direction in which the wind is blowing.

14. In para 11, several new terms were introduced, eg true airspeed, track, and groundspeed. These will now be examined in more detail.

Airspeed

15. The speed of an aircraft measured relative to the air mass through which it is moving is termed true airspeed (TAS). It is emphasised that, because of wind velocity, this speed will differ from that measured by an observer on the Earth. Airspeed is independent of wind, and is the same regardless of whether the aircraft is flying upwind or downwind.

16. An aircraft's airspeed is usually measured by an airspeed indicator (ASI). The ASI reading is termed indicated airspeed (IAS), but this does not equal true airspeed. The difference between these quantities is caused by a number of inaccuracies which, broadly speaking, stem from two sources, the ASI itself and the atmosphere.

17. If IAS is corrected for the inaccuracies of the ASI (instrument and pressure errors), the result is called calibrated airspeed (CAS). At higher speeds (normally above about 300 kt), a correction to CAS is necessary to take into account the compressibility of air; this correction varies with altitude and speed. The speed after this correction is termed equivalent airspeed (EAS). ASIs are calibrated in relation to the International Standard Atmosphere and at mean sea level. At all other altitudes, EAS and CAS are less than TAS because the air is less dense than at sea level. CAS or EAS may be corrected to TAS by using graphs, tables, digital computers or analogue computers (such as the Dead Reckoning Computer Mk 4A).

Mach Number

18. An alternative method of quoting TAS is to express it as a fraction of the local speed of sound; this fraction is known as the Mach Number (M) and is given by:

$$M = \frac{V}{C}$$

Where V = True Airspeed
C = Speed of Sound (in the same air conditions)

Mach Numbers are expressed as decimals e.g.:

V = 440 kt and C = 580 kt, then M = 0.76; or
V = 725 kt and C = 580 kt, then M = 1.25.

19. There are aerodynamic problems which occur at a certain fraction (depending on the aircraft type) of the speed of sound. Although this fraction is fixed, it may be represented by widely varying values of CAS (depending on altitude) and varying values of TAS (depending on temperature). It is more convenient, therefore, in high-speed flight to display the aircraft's speed as a Mach Number rather than as IAS or TAS. A Machmeter computes and displays this quantity.

20. The speed of sound varies as the square root of the absolute temperature. Thus, the calculation of TAS from Mach Number is much simpler than, say, from CAS, for the only variable is temperature.

Groundspeed

21. Since air navigation is concerned with the movement of an aircraft over the Earth, it is necessary to know the speed at which the aircraft is moving relative to the Earth; this is termed groundspeed and, like airspeed, it is measured in knots.

22. Groundspeed is usually determined by one of the following methods:

a. Calculating the effect of wind velocity on the aircraft, ie by solving the triangle of velocities.

b. Measuring the time taken to travel a known distance between two positions on the ground.

c. The use of Doppler equipment.

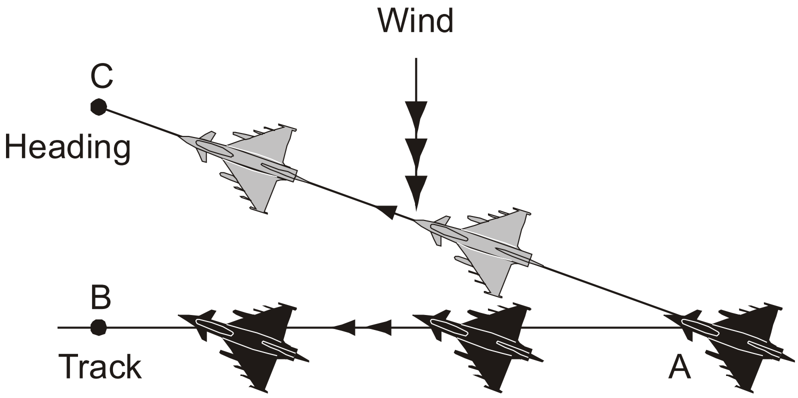
d. The use of inertial navigation systems.

Track

23. The direction of the path of an aircraft over the ground is called its track. If an aircraft flies directly upwind or downwind, or in still air, its path over the ground lies in the same direction as its heading. In all other cases, wind will cause the aircraft to move over the ground in a direction other than that which is in line with its fore and aft axis, and to an observer on the ground it will appear to move crab-wise rather than straight ahead. In such cases the aircraft's heading and track are not the same.

24. In Fig 5, an aircraft at A is flying on a heading of 290° (T). As it maintains this heading, a northerly wind carries the aircraft from the path it would have followed in the absence of the wind ie AC. Sometime later the aircraft passes over B; AB then represents the track and the aircraft is said to have 'tracked' from A to B.

9-4 Fig 5 Heading and Track

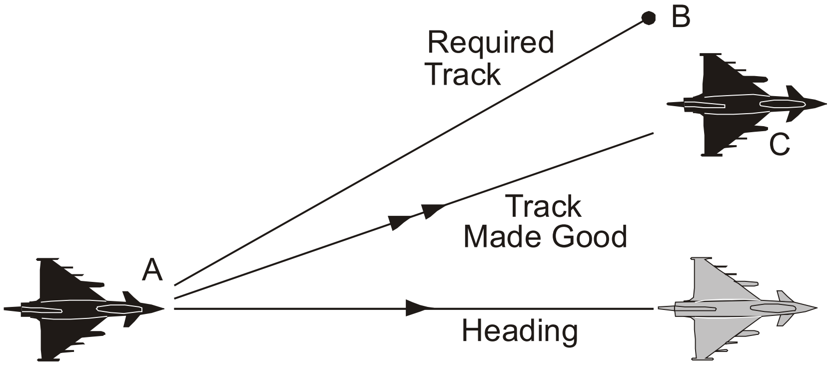


25. The line joining two points between which it is required to fly is known as the required track.

26. In flying from one point to another, the path which the aircraft actually follows over the ground is called its 'track made good'. When track made good coincides with required track, the aircraft is said to be 'on track'; when track made good and required track are not the same the aircraft is said to be 'off track'.

27. Fig 6 illustrates the difference between required track and track made good. An aircraft attempting to go from A to B finds itself some time later at C. AB is therefore the required track and AC the track made good.

9-4 Fig 6 Required Track and Track Made Good



28. Any two points on the Earth's surface may be joined by a rhumb line and by a great circle. It follows, therefore, that the required track may be either a rhumb line track, which follows the rhumb line between two points, or a great circle track, which follows the great circle between the points. By definition, the rhumb line track maintains a constant direction relative to true North and is therefore, in many cases, the easier to make good.

29. Track is measured in degrees and is expressed (like heading) as a three-figure group eg 045°. Track may be measured relative to true North, magnetic North or grid North and is annotated (T), (M) or (G) accordingly.

Drift

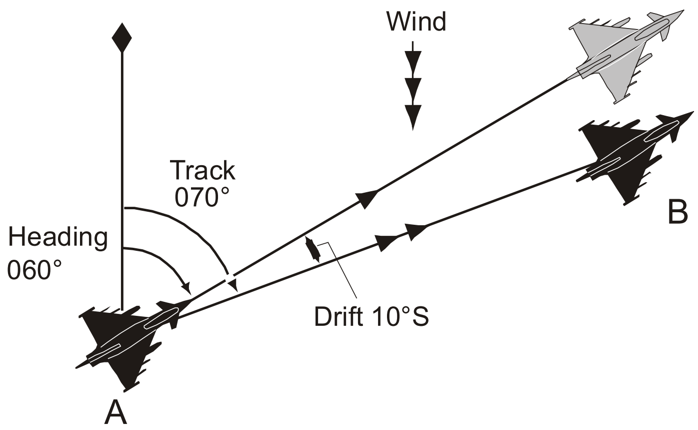
30. The angle between the heading and track of an aircraft is called drift. Drift is due to the effect of the wind and is the lateral movement imparted to an aircraft by the wind. An aircraft flying in conditions of no wind, or directly upwind or downwind, experiences no drift. In such cases, track and heading coincide. Under all other conditions, track and heading differ by a certain amount, referred to as the drift.

31. Drift may be measured manually by observing the direction of the apparent movement of objects on the ground below the aircraft (Track) and comparing this direction with the fore and aft axis of the aircraft (Heading) to obtain the angular difference (Drift). Many aircraft are fitted with automatic systems that calculate drift continuously by electronic means eg Doppler or inertial systems.

32. Drift is expressed in degrees to port (P) or starboard (S) of the aircraft's heading. An aircraft experiencing port drift is said to drift to port, and its track lies to port of its heading. Thus, knowing the heading of the aircraft, the track can be determined by proper application of drift to heading. If drift is to port, track angle is less than heading; if to starboard, track angle is greater than heading. Automatic systems can continuously apply drift to heading to give a direct indication of track.

33. The direct measurement of track, i.e. from knowledge of actual ground position, enables drift to be determined, provided the heading is known. Thus, an aircraft whose track is measured from a map as 070° (T) while flying on a heading of 060° (T) is drifting 10° to starboard. This relationship is shown in Fig 7.

9-4 Fig 7 Drift



APPLICATION OF THE TRIANGLE OF VELOCITIES IN NAVIGATION

General

34. Having discussed the triangle of velocities and its components, it is now possible to review its application in the solution of navigation problems.

35. The triangle of velocities may be considered to have six parts; each of its three sides representing a speed and a direction. A knowledge of any four of these parts enables the remaining two parts to be found. In navigation, the types of problem solved by this method are:

a. Finding the length and direction of one side eg finding track and groundspeed, wind velocity or, occasionally, heading and airspeed.

b. Finding the length of one side and the direction of another, eg true heading and groundspeed.

In practice, the triangle of velocities can be continuously resolved by automatic navigation systems. However, graphical methods may still be used during planning and in flight, using the transparent plotting disc of the DR Computer Mk 4A or Mk 5A. The following examples, employing basic pencil-on-paper vector plotting, are therefore intended to provide a thorough understanding of the underlying principles, rather than to illustrate a practical method of solving navigation problems.

Rules for Plotting

36. In plotting the vector triangle, there are a number of points to note. The same datum direction, and a uniform unit of measurement, must be used for all vectors, otherwise the diagram will be distorted. Furthermore, one must ensure that true airspeed is measured only along true heading and that similar relationships for track and groundspeed, and wind direction and wind speed are maintained.

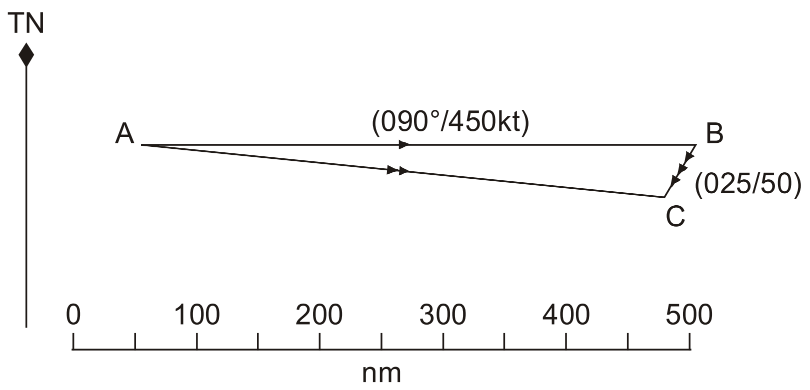
Finding the Length and Direction of One Side

37. **To Find Track and Groundspeed**.

Example: An aircraft flying at TAS 450 kt, on a heading of 090° (T), experiences a w/v of 025°/50 kt. What is its track and groundspeed?

Solution (Fig 8):

9-4 Fig 8 Calculating Track and Groundspeed



a. Draw AB, the heading and airspeed vector.

b. From B, lay off the wind vector BC.

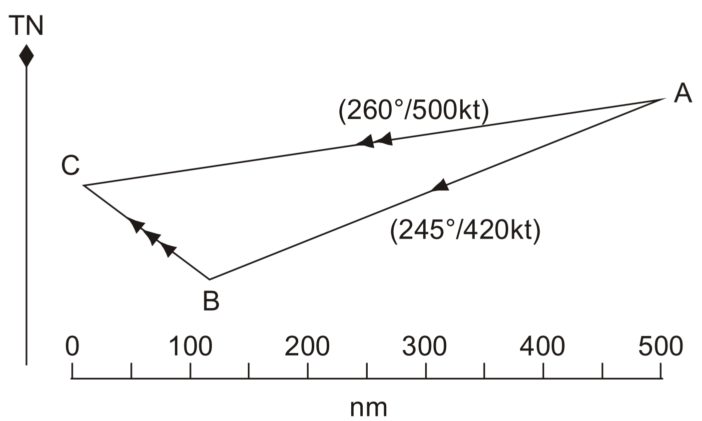
c. Join AC, and measure its direction and length. Track and groundspeed are found to be 096° (T) and 432 kt respectively.

38. **To Find Wind Velocity**.

Example: The groundspeed of an aircraft is 500 kt on a track of 260° (T); its true airspeed is 420 kt on a heading of 245° (T). What is the wind velocity?

Solution (Fig 9):

9-4 Fig 9 Finding Wind Velocity



a. Plot AB, the heading and true airspeed vector.

b. From A, lay off AC, the track and groundspeed vector.

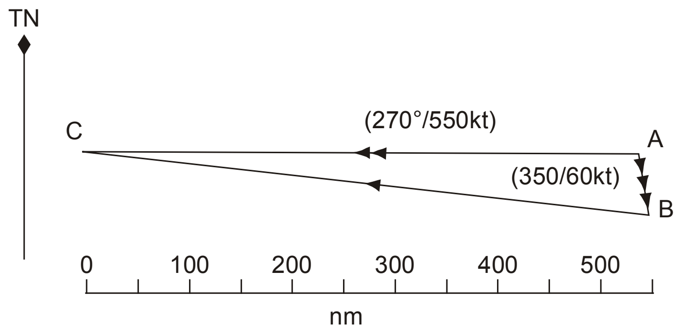
c. Join BC and measure its direction and length. Wind velocity found is 129°/145 kt.

39. **To Find True Heading and True Airspeed**.

Example: In order to maintain a schedule it is necessary to fly a track of 270° (T) at a groundspeed of 550 kt. The wind velocity is 350°/60 kt. What true airspeed and what true heading must be flown to achieve these conditions?

Solution (Fig 10):

9-4 Fig 10 Finding True Heading and Airspeed



a. Plot AB, the wind vector.

b. From A, lay off AC, the track and groundspeed vector.

c. Join BC to obtain the heading and airspeed vector. Heading and airspeed are 276° (T) and 563 kt respectively.

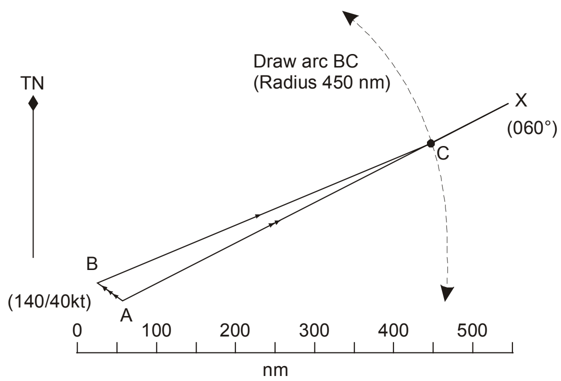
Finding the Length of One Side and the Direction of Another

40. **To Find Heading and Groundspeed**. The determination of the heading to make a given track, and the resultant groundspeed, is probably the most common navigation problem:

Example: It is necessary to make good a track of 060° (T) whilst flying at a TAS of 450 kt. Wind velocity is 140°/40 kt. What heading must be flown and what groundspeed will be achieved?

Solution (Fig 11):

9-4 Fig 11 Finding Heading and Groundspeed

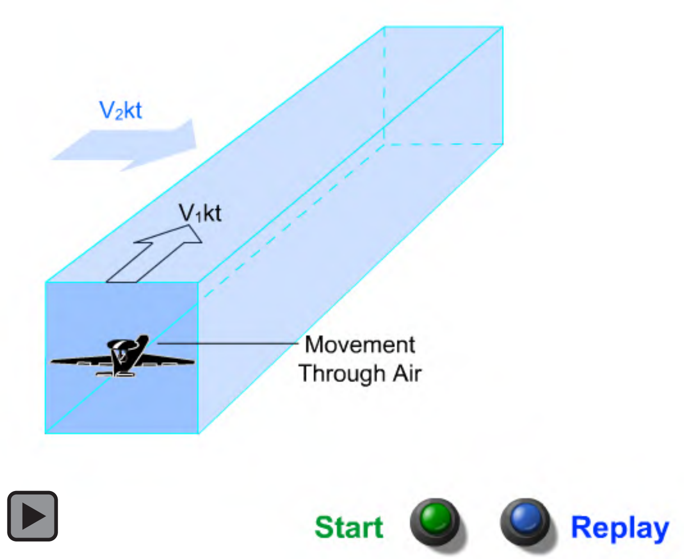


a.	Draw line AX of indefinite length in a direction 060° (T) to represent required track.

b.	From A, lay off AB, the wind vector.

c.	With centre B, and radius true airspeed, describe an arc to cut AX at C. The direction of BC, 065° (T), is the heading required to make good a track of 060° (T); AC represents groundspeed, which is measured as 441 kt.

Fig 2 - Factors Affecting the Path of an Aircraft (Return to text)



CHAPTER 5 - DETERMINATION AND APPLICATION OF WIND VELOCITY

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DETERMINATION

Introduction

1. Wind velocity plays a major part in navigation calculations. If wind velocity was constant, one measurement would suffice for all calculations and workloads would be considerably reduced. However wind velocity is seldom constant; it varies in direction and speed with height, time, and place. Consequently, a knowledge of the expected wind velocities is required in order to plan a flight, a knowledge of the wind effect actually being experienced in flight is necessary to calculate position and a knowledge of present wind velocity is needed to calculate alterations of heading. Because of its continual variation, it is normally necessary to measure wind velocity frequently if accurate navigation is to be accomplished.

Mean and Local Wind Velocities

2. Measured wind velocities may be divided into mean and local winds, the division depending upon the interval over which the wind is determined. A mean wind velocity is one which has been found over a fairly long time period and usually over a large area; it represents the mean effect of all the different wind velocities experienced by the aircraft during that time. However, should the wind velocity have changed during the period of measurement, the mean wind velocity may be quite different from the actual wind velocity affecting the aircraft at the end of the period. Consequently although a mean wind velocity is ideal for calculating position, it is not usually suitable for calculating alterations of heading, because it may not represent the wind velocity that will affect the aircraft to its next turning point or destination.

3. A wind velocity found instantaneously, or over a comparatively short period of time, is known as a local wind velocity. It represents the wind velocity affecting the aircraft at that time and as such is usually the best available wind velocity for use in calculating alterations of heading.

4. In practice, it is usually necessary to compromise between mean wind velocities found over long periods of time and the more quickly calculated local wind velocity. Whereas the former are of limited value for future application, the latter tend to be less accurate because the time interval in which they are measured is small. The actual period of time that will provide a reasonable value of wind velocity is a matter of judgement. For example, if the wind velocity was required in order to calculate a change of heading, it would be inappropriate to use a time period during which there had been a significant change in height or during which a weather front had been crossed. In normal circumstances, wind velocities found over time periods between 18 minutes and 40 minutes are used.

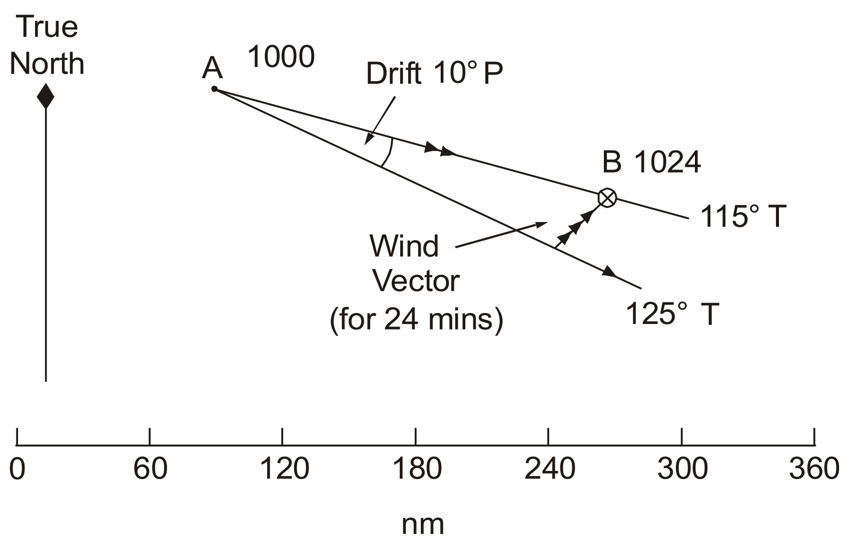
5. Modern navigation systems provide an instantaneous readout of local W/V which can be used to compare against the forecast W/V or to calculate required heading changes if necessary. Although manual plotting techniques are rarely practised nowadays, where they are used, several methods of determining W/V can be employed, and the following paragraphs may provide a useful background to the basic understanding of navigation. It should be appreciated that the results obtained by each method described in the following paragraphs will be different.

Track and Groundspeed Method

6. The track and groundspeed method is that solution of the vector triangle which determines the length and direction of one side of the triangle (the wind vector), given the length and direction of the other two sides (the heading and track vectors). The wind velocity so found may be a mean wind velocity, or a local wind velocity, depending upon the time interval chosen.

7. The principle of the method is illustrated in Fig 1. An aircraft leaves point A at 1000 hours, on a heading of 125º T and with a TAS of 420 kt. At 1024 hours, the aircraft's ground position is found to be at point B, which bears 115º T from A, at a distance of 180 nm. The aircraft's ground speed can thus be calculated as 450 kt and the drift as 10º P. Heading, TAS, drift and groundspeed can be set on to a DR computer and wind velocity found as 231º/82 kt.

9-5 Fig 1 Track and Groundspeed Wind Velocity



8. When using this method no alterations of heading or airspeed can be tolerated between the fixes used in determining the track and groundspeed. An alteration of heading between the two fixes will result in the measurement of an erroneous track and groundspeed and consequently an incorrect wind velocity. Similarly an alteration of airspeed will cause errors because the resultant changes in drift and groundspeed will be attributed to the wind effect.

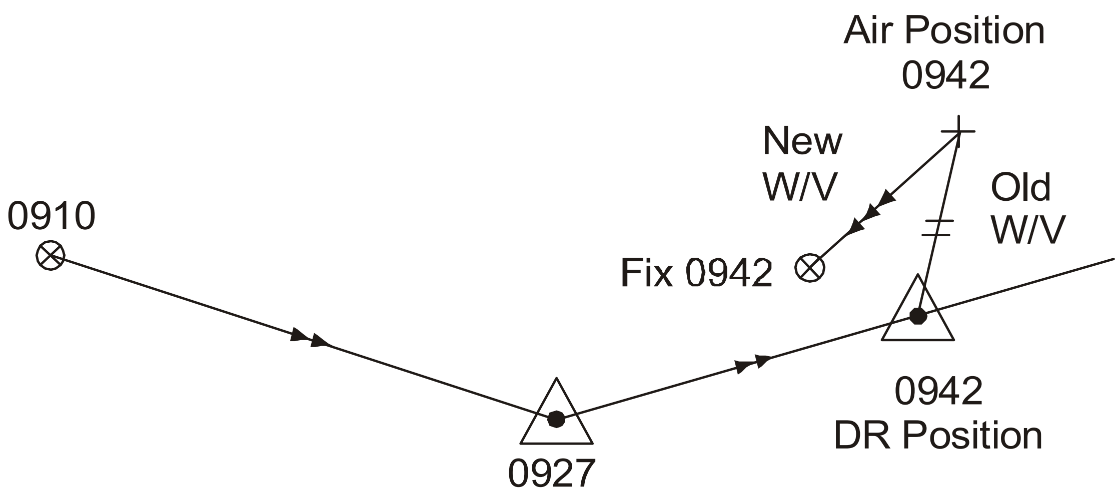
9. The track and groundspeed method of finding wind velocity eliminates the plotting and measurement of wind vectors, which is often a major source of error, and so its accuracy depends primarily on the accuracy of, and measurement between, the fixes used to determine the track and groundspeed. Other pertinent factors are the accuracy to which true heading is known, the accuracy of timing and computation, and the pilot's ability to maintain a constant heading and airspeed.

10. **Automated Wind Velocities**. None of the limitations mentioned in paras 8 and 9 apply to wind velocities found from the continuous outputs of drift and groundspeed provided by automated navigation equipments. These quantities may be applied to true heading and true airspeed to find the local wind velocity. The advantages of this method are that the wind velocity currently affecting the aircraft can be quickly, easily and continuously determined, consequently there is little restriction on tactical freedom.

Track Plot Wind Method

11. When keeping a track plot, winds are normally found by the track and groundspeed method. If, however, a fix is found from which neither groundspeed nor track can be calculated, the wind velocity may be determined by back plotting vectors in the following manner. In Fig 2, a fix has been found shortly after a change of heading. A DR position, using the old wind velocity is plotted for the time of the fix. The reciprocal of the old wind velocity is laid off from this DR position, making the length of the vector proportional to the time that has elapsed since the start of the track plot, to produce an air position. The new wind velocity for the same period of time is given by joining this air position to the fix. Alternatively, by joining the fix to the DR position for the same time, a correction vector for the old wind velocity may be obtained.

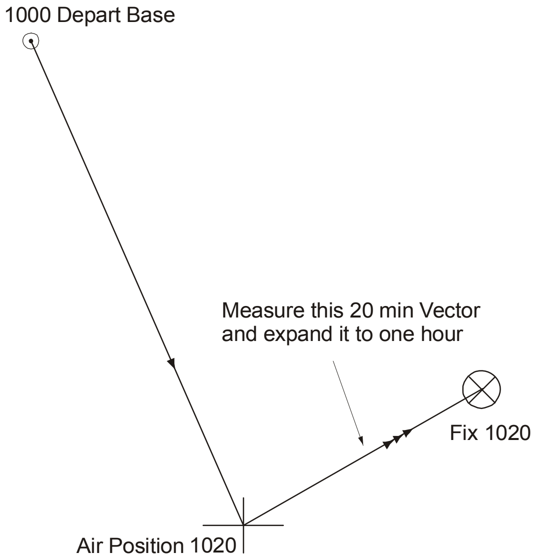
9-5 Fig 2 Track Plot Wind Vectoring



Air Plot Wind Method

12. The air plot method does not rely on the measurement of track and groundspeed, instead the wind vector, ie the displacement between a fix and its corresponding air position, is measured directly (Fig 3). The wind vector measured is of course proportional to the period of time that the air plot has been running, and must be converted mathematically to nautical miles per hour (ie a wind velocity in knots).

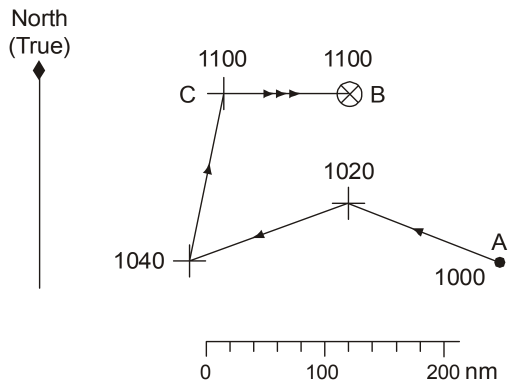
9-5 Fig 3 Air Plot Wind Velocity



13. Whereas the track and groundspeed method of finding wind velocity cannot be used if there is any alteration of heading or airspeed between the fixes, this restriction does not apply to the air plot method. Wind velocities can be measured, regardless of heading and airspeed flown, provided that an accurate log of air positions is maintained for each change of heading or airspeed. The plot must be restarted whenever a fix is obtained and the navigation equipment updated.

14. As an example, in Fig 4, an aircraft flying at a true airspeed of 420 kt leaves point A at 1000 hours and flies for 20 minutes on each of three headings, 290º T, 250º T, and 010º T. At 1100 hours the aircraft's position is fixed at point B, and from the log of heading and airspeed, an air position for the same time can be established at point C. The vector CB is the wind effect for an hour, and it represents the average of the wind velocities which have affected the aircraft over the hour; it can be measured as 269º/105 kt.

9-5 Fig 4 Air Plot Wind Velocity Incorporating Changes of Heading



15. The accuracy of the air position, which depends on the accuracy of the start fix and the knowledge of headings and airspeed flown, together with the accuracy of the final fix, dictates the accuracy to which the wind velocity can be determined.

16. An air plot wind is the mean wind velocity over the period since the air plot was started and thus its validity for future calculations must be considered carefully. It is usually necessary for this reason to limit the period over which air plot winds are found in order to obtain an approximation to the local wind.

17. Conversely, if air plots winds are found over very short intervals, the resultant vectors are often so short that accurate measurement is difficult. Errors in measuring vectors, representing short periods of wind effect, cause large errors in the wind speed found, e.g. an error of 1 nm in a vector representing a 6 minute period will result in a 10 knot inaccuracy. Usually the most satisfactory period for wind finding is between 18 minutes and 40 minutes.

Visual Wind Assessment

18. When flying at low level, in sight of the surface, it may be possible to make an assessment of the wind direction, and with experience also of the wind speed, by observing its effect on smoke plumes from factories, power stations and other miscellaneous fires. It should be remembered that close to the surface there may be local wind channelling and eddies, and the apparent wind direction may not be a true representation of the mean wind over a broader area or at the aircraft's height. Despite these shortcomings, such clues can be helpful where there is little better information, or where it is required to confirm a forecast wind velocity. Over open water, the wind causes a pattern of parallel lines or streaks formed by foam or spray. These streaks, called wind lanes, are aligned with the wind direction and are usually clearly visible from the air.

APPLICATION

Introduction

19. Generally speaking, wind velocities found by the methods described in the previous paragraphs are used directly in the calculation of future headings, and DR groundspeed. It is, however, sometimes necessary to apply corrections to the wind found before it is used in further navigation calculations. The occasions requiring such corrections are dealt with in the following paragraphs.

Change of Meteorological Zones in Flight

20. Where the meteorological forecast for a particular flight is divided into a number of zones, it will be necessary to take into account the change in wind to be expected on crossing the boundary between zones. This is done by comparing the wind velocity found with that forecast, for the zone in which the aircraft has been flying. The arithmetical difference in both direction and speed is then applied to the wind forecast for the next zone.

> Example. A met forecast for zones 1º E to 5º E and from 5º E to 10º E gives wind velocities of 250º/20 kt and 270º/30 kt respectively. Approaching 5º E from the west, the wind is found as 235º/15 kt. The difference between the met forecast and the wind found in the first zone is therefore –15º and –5 kt. This correction factor is applied to the forecast wind for the second zone, giving a wind to be used as 255º/25 kt.

21. This procedure is applicable to navigation in areas where few fixes are available, whereas in rapid-fixing areas local wind velocities found regularly over relatively short periods would be used without corrections.

Change of Height in Flight

22. The method of selecting a wind velocity for use after the aircraft has changed height is similar to that outlined above. A correction factor, being the difference between the forecast and found winds at the height flown, is applied to the forecast wind velocity for the new height to be flown.

23. In the event of the aircraft making a long climb, it may be necessary to alter heading while ascending, and therefore to select a wind velocity for that part of the climb from the DR position at the time of altering heading to the limit of the ascent. Wind velocities found whilst climbing are mean wind velocities (apart from those found by automated equipments) and the height at which they are considered to be operative is ascertained by the application of simple rules which depend upon the rate of climb of the aircraft.

24. If the rate of climb is constant throughout the period in which the wind velocity is found, the wind velocity is said to apply to the mean height for the period. If the rate of climb is decreasing during the period in which the wind velocity is found, the wind applies at two-thirds of the height band ascended during the period.

> Example. A wind velocity of 240º/30 kt is found whilst an aircraft is climbing from 7,000 ft to 16,000 ft, and during that time the rate of climb decreases. Therefore 240º/30 kt is the wind velocity applicable to a height at two-thirds of the ascent from 7,000 ft to 16,000 ft, ie 13,000 ft.

25. Two-thirds is an arbitrary fraction designed to take some account of the fact that the aircraft, with a decreasing rate of climb, spends more time in the higher layers of air and is therefore affected to a greater degree by wind velocities at the higher levels.

26. Having established, in the above example, that the wind velocity at 13,000 ft is 240º/30 kt, it is necessary to select a wind velocity for the remainder of the climb, say to 22,000 ft. Since the rate of climb continues to decrease with height, the two-thirds rule is again applied and a wind velocity is therefore required for 20,000 ft, ie two-thirds of the ascent from 16,000 ft to 22,000 ft. The procedure for selecting this wind is as described in paras 24 and 28.

Wind Velocity for Flight Planning a Climb or Descent

27. The wind velocity to be used when flight planning a climb or descent is the mean of the wind effects which will be experienced by the aircraft as it ascends or descends through the various layers of air. The selection of this wind velocity, in practice, depends upon the change of wind speed and direction with height, and upon the rate of climb or descent of the aircraft. Where the wind velocity changes regularly with height and the rate of climb or descent is constant, the wind velocity at the mid-level would be used; where the rate of climb reduces with altitude the level chosen would need to reflect the longer time spent at the higher altitudes and the two-thirds rule will normally suffice, although this may need to be amended for certain aircraft types and payload. Where there is an intermediate fix (or fixes), in the climb or descent, an appropriate wind velocity for each section can be used.

28. Example. Consider an aircraft which is to climb from 2,000 ft to 27,000 ft at a constant rate of climb. The forecast wind velocities are as follows:

2,000 ft	220º/15 kt
5,000 ft	230º/25 kt
10,000 ft	240º/30 kt
15,000 ft	260º/40 kt
20,000 ft	290º/50 kt
30,000 ft	350º/70 kt

29. These wind velocities vary regularly with height, and since the rate of climb is constant, the wind for the mean height of the climb would be used, ie that effective at 12,500 ft - 250º/35 kt.

30. If the aircraft was to climb from 2,000 ft to 27,000 ft at a reducing rate of climb, the two-thirds rule would be applied to determine the appropriate height, ie 18,500 ft in this case, giving a wind velocity of 280º/47 kt to be used. In practice, the 20,000 ft wind velocity would probably suffice to avoid interpolation.

31. A further adjustment may be necessary in the situation where the wind velocity does not vary uniformly with height, but exhibits a marked change at some level, perhaps due to a jet stream. In any event the wind velocity that is used will inevitably be an approximation, and even the simple case of a constant rate of climb or descent may be disrupted by Air Traffic Control restrictions.

CHAPTER 6 - ESTABLISHMENT AND USE OF POSITION LINES

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Table

Terminology

1. A position determined without reference to any former position is called a fix. This is a generic term and is often qualified to indicate the fixing method, e.g. GPS fix, radar fix, visual fix etc.

2. Instantaneous fixes can be obtained from electronic navigation systems or the visual identification of the aircraft position vertically beneath the aircraft. Electronic rapid fixing facilities are not infallible, and position lines can be used to enhance confidence in them. While position lines are not generally plotted on charts nowadays, some operators may still use such traditional navigation techniques.

3. It is possible to fly over an identifiable feature, e.g. a motorway, without knowing the precise point of crossing; all that can be said is that at that particular time the aircraft was somewhere on the line of the motorway. This is known as a position line (P/L) and two or more such lines can provide a fix.

POSITION LINE TYPES

General

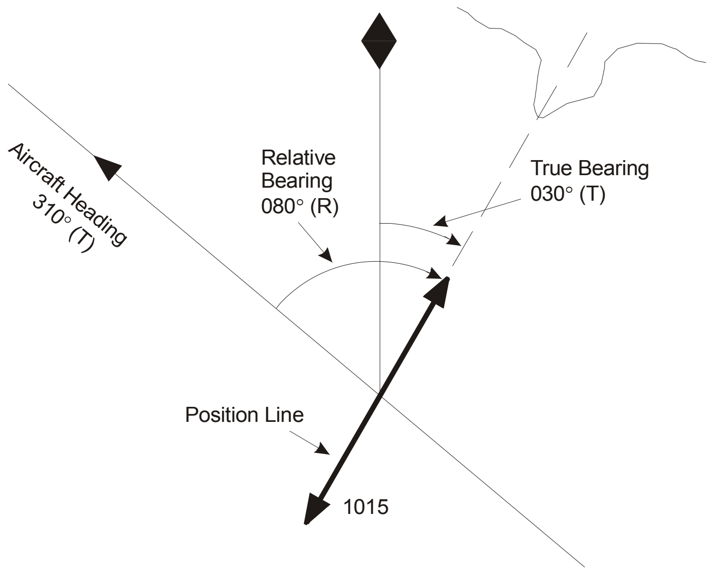
4. Position lines can be straight or curved, depending on the information they convey. Bearings are straight position lines representing the angular relationship between the aircraft and a known position, or the orientation of a line feature. Circular position lines represent the aircraft's range from a position, the radius of the curve being equal to the range. Both forms of position line and their sub-classifications are discussed below.

Bearings

5. **Relative Bearings**. A bearing may be taken relative to the fore and aft axis of the aircraft, normally by using a radio compass tuned to a radio beacon or by visual or radar observation of a feature. To obtain the true bearing of the beacon or feature, the true heading of the aircraft must be added to the relative bearing (either directly or by offsetting the azimuth scale of the measuring instrument). The reciprocal of this true bearing plotted from the beacon or feature gives the position line for the time of observation. It is essential that the true heading applied to the relative bearing is obtained at the precise time of the observation.

Example. At 1015 hours, while on a heading of 310° T, a prominent headland is observed on a bearing of 080° relative (see Fig 1).

9-6 Fig 1 A Relative Bearing



∴True bearing of headland from aircraft = 080° + 310° = 030° T

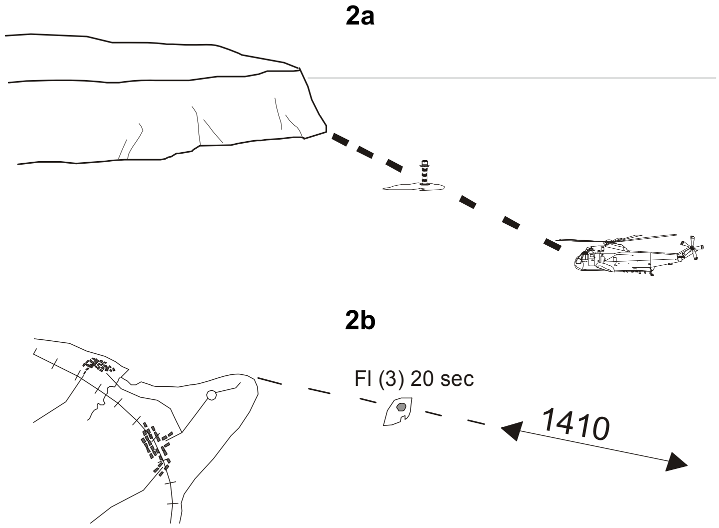
Plot reciprocal: 030° T + 180° = 210° T.

At 1015 hours, the aircraft was therefore at some point along that position line.

6. **Transit Bearings**. A line drawn on a chart through two features observed to be in line, i.e. in transit, must pass through the aircraft's position at the time of sighting. This line, a true bearing, is therefore a position line.

Example. A lighthouse and a promontory of land are sighted in transit at 1410 hours (see Fig 2a). The position line is drawn as in Fig 2b, though the dotted portion need not be plotted. Greater accuracy is obtained when the distance between the objects in transit is large in relation to the distance between the aircraft and the nearer object.

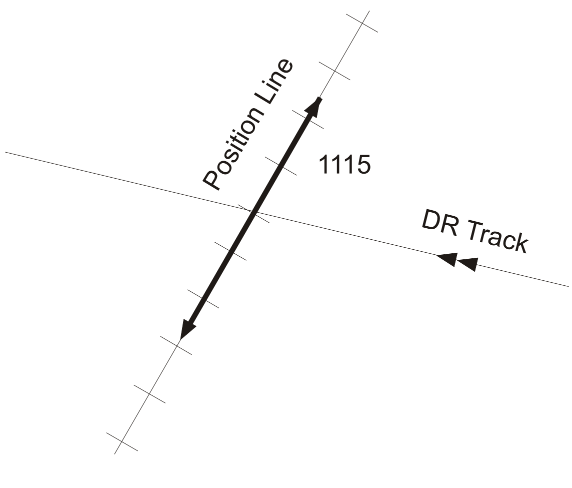
9-6 Fig 2 A Transit Bearing



7. **Line Features**. Stretches of coastline, road, railway or river, though lacking prominent features suitable for pinpoints, may be used as position lines provided that they are marked on the charts in use.

Example. An aircraft crosses a straight stretch of railway at 1115 hours. The railway thus becomes the position line as shown in Fig 3.

9-6 Fig 3 Use of Line Features



8. **Position Lines from Ground D/F Stations**. A position line may be obtained by a direction-finding ground station taking a bearing on an aircraft's radio transmission. The bearing is passed to the aircraft by radio, usually in the form of either the true bearing of the aircraft from the station, or as the magnetic track that the aircraft must make good to reach the station. The form is decided by the

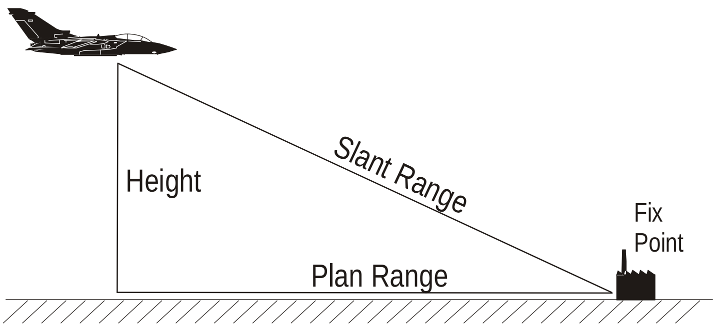
initial call: "request true bearing" or "request QDM" (magnetic heading to facility (zero wind)). In order to use the latter information, the magnetic variation, measured at the station, must be applied, so obtaining the true track to the station; the reciprocal is then plotted. The other information which can be provided by the ground D/F station is the magnetic heading to fly to reach that station; this is termed a 'steer'. Using a local wind velocity, the ground operator assesses the drift and applies this to the QDM measured, to calculate the steer for the aircraft. Ground D/F facilities are provided on VHF and UHF within the UK, but the service may be available on other bands elsewhere.

9. **TACAN and VOR Bearings**. TACAN and VOR beacons both transmit a signal which, when interpreted by the aircraft equipment, gives the magnetic bearing of the aircraft from the beacon. The position line is obtained by taking the reciprocal of the reading of the indicator needle.

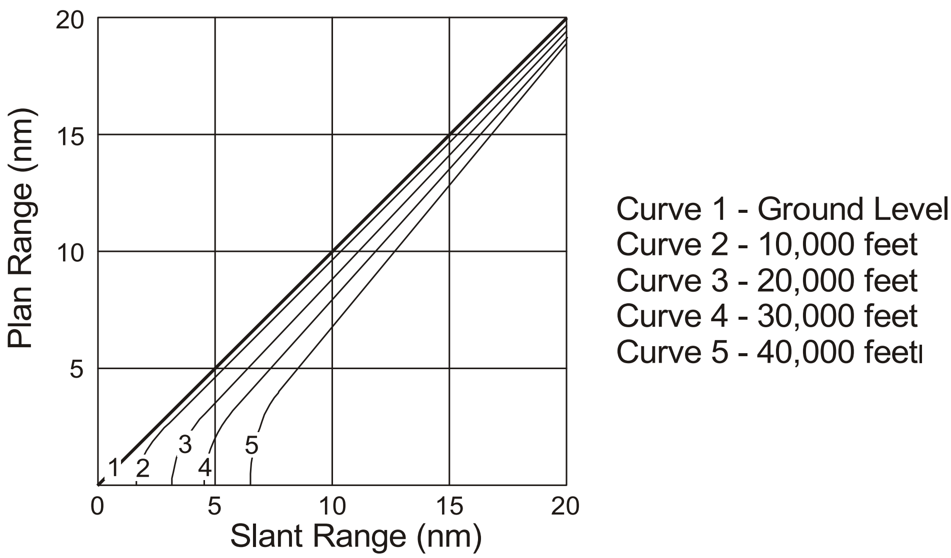
Circular Position Lines

10. **Radar Range Position Lines**. The range from a ground TACAN or DME beacon can be obtained using transmitter/responder equipment. The range displayed is a slant value (Fig 4), which should be converted to plan range before plotting. Fig 5 shows a typical slant range to plan range conversion graph. The circular position line is drawn with the plan range as radius and with the beacon as the centre. Range position lines may also be obtained by ground mapping radars, in some of which the range is automatically converted to plan range. However more simple equipments, such as cloud warning radars, give slant range only which should be corrected in the same way as TACAN and DME ranges.

9-6 Fig 4 Slant Range



9-6 Fig 5 Slant to Plan Range Conversion



USE OF SINGLE POSITION LINES

Introduction

11. A single position line can be used to provide navigation data in one or more of the following ways:

a. As a check on groundspeed.

b. As a check on ETA.

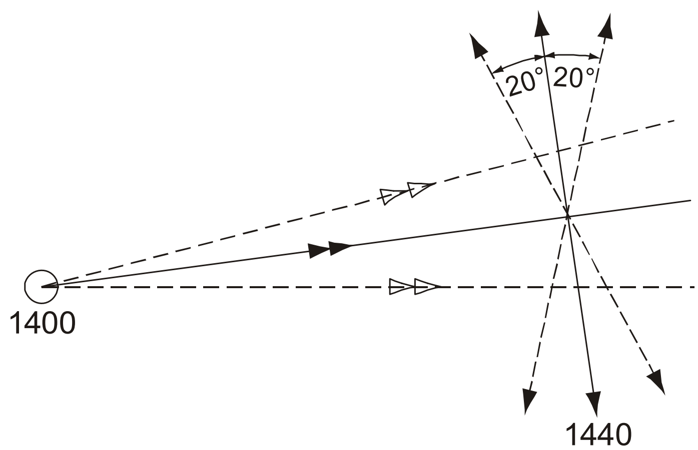
c. As a check on track made good.

d. As a means of homing to an objective.

Groundspeed Check

12. For a groundspeed check, a position line is required which lies as nearly as possible perpendicular to the aircraft's track (see Fig 6).

9-6 Fig 6 Position Line used forGroundspeed Check



13. The distance between the last fix and the position line is measured along the DR track, and so, knowing the time that has elapsed, the groundspeed can be calculated. If the position line is within ±20° of the perpendicular to track, then errors in DR track (represented by the broken track lines in Fig 6) will produce little difference in the distance measured and therefore no significant error in the groundspeed calculated.

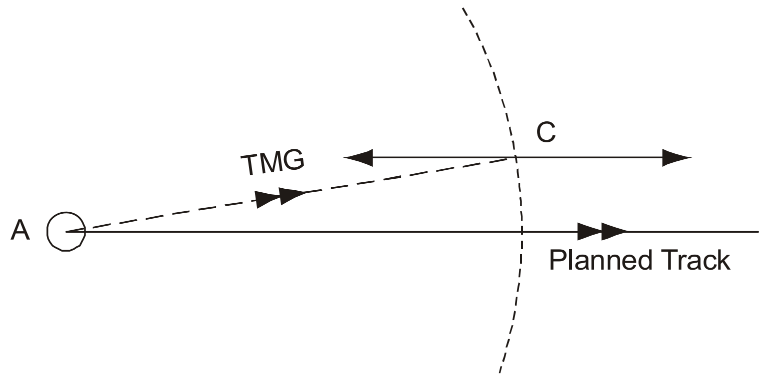
ETA Check

14. A position line near the perpendicular to track may provide a check of ETA at the next turning point by enabling the distance to run to be measured accurately.

Track Check

15. To check track made good, a position line is required which is parallel or nearly parallel (±10°) to DR track (see Fig 7).

9-6 Fig 7 Position Line used for Track Check



16. In Fig 7, an arc equal in radius to the ground distance flown since the last fix (position A), calculated using the latest groundspeed, is described from that fix to cut the position line at C. AC then represents the track made good. Errors in the groundspeed used will cause an error in the position of C along the position line, but this error will have little effect if the limits of para 15 are observed.

Homing Check

17. Homing to a destination along a position line, whose origin is the destination, is a simple matter, since the direction of the position line is the same as that of the required track. The aircraft is turned on to a heading which will make good this track and tracking can be checked against further position lines obtained from the destination.

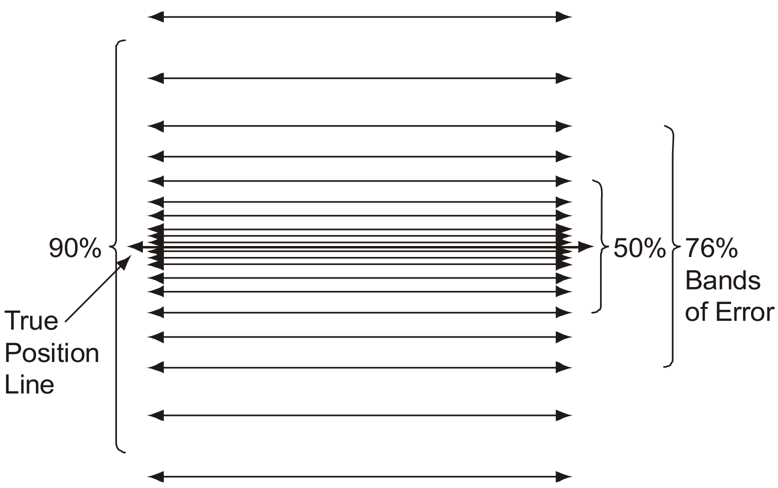
Accuracy of Position Lines

18. When a position line is obtained, it is assumed, for the purposes of navigation, that the aircraft's position is on that line at that particular time. However, in practice, the aircraft is very seldom exactly on that line at the time it was obtained. All position lines are subject to errors, the magnitude of which depends upon the type of position line, i.e. whether it is a visual bearing or an electronically derived bearing, and the conditions under which it is obtained.

19. If a large number of position lines of the same type could be taken from an aircraft in the same known position, and operating under identical conditions, the position lines when plotted would be found to lie in a band about the aircraft's true position. They would be found to be concentrated in the area about the aircraft's position and would become more widely dispersed with distance away from the aircraft.

20. This dispersion of results is due to a variety of reasons, eg slight errors in timing and observation, approximations in calculations. It is possible to carry out a statistical analysis on a set of accuracy figures for position lines of any type, and from this, to define the width of the band about the true position which would enclose a certain proportion, say 50%, 70% or 90% of all the position lines considered (see Fig 8).

9-6 Fig 8 Statistical Distribution of Observed Position Lines



21. The bands are known as bands of error in navigation terminology, and the 50% and 76% bands are those normally considered. Extensive trials have been carried out on the accuracy of position lines and as a result it has been possible to produce a table which defines, for convenience, half the width of bands of errors for various types of position lines (see Table 1).

Table 1 Position Line Bands of Error

Type of Position Line		Band of Error (Half - Widths) 50%	76%
Transit Bearing		0.5°	0.9°
TACAN Bearing		2°	3.5°
TACAN/DME Range		0.2 nm	0.5 nm
VOR		3°	5°
ADF		1.5°	2.5°
Cloud Warning Radars:	a. Range	2 nm	3 nm
	b. Bearing	3°	5°

22. Taking the 50% band as an example, this band encloses 50% of all possible position lines, and there is, therefore, only an even chance of being somewhere inside the band of error. The 76% band is wider since it must contain a larger number of possible position lines and if this band is plotted there is a 76% chance of being somewhere inside it. To cover every possible case the 100% band of error would need to have infinite width, since gross errors would inevitably occur in a few cases in the calculating and plotting of a large number of position lines. It is clearly impracticable to work at very high levels of probability and, indeed, a position line that falls a considerable distance from its expected position should be treated with circumspection and its accuracy should be verified by other means if possible.

CHAPTER 7 - PLOTTING POSITION LINES

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Introduction

1. Position lines are not generally plotted onto charts nowadays but where they are used, this chapter will provide the necessary information to allow the user to employ them correctly. The line of sight between two points lies along the shortest path between them. The corresponding radio wave also follows the same path. Consequently, visual and radio bearings are great circles, and this complicates plotting for none of the common plotting charts portray all great circles as straight lines.

2. The divergence (Δ) between the straight line joining two points on the chart, and the corresponding great circle varies according to:

a. The projection.

b. The bearing and distance between the two points.

c. The area of operation.

3. **The Projection**. The path represented by a straight line on a chart depends upon the projection employed in the chart's construction. On some projections, the straight line approximates to a great circle, while on others it is very different. Consequently, the magnitude of the angular divergence between the straight line and the great circle is a function of the projection being used. Loosely speaking, ignoring both the effect of the relative orientation of the two points and the area of operation, the divergence is greater on the Mercator projection than on the other common projections: the polar stereographic, the Lambert's conformal, the oblique and transverse (skew) Mercators. On the Mercator projection, the straight line represents the rhumb line.

4. **The Relative Orientation of the Two Points**. A straight line can represent more than one path on a projection. For example on the Mercators, Lamberts and polar stereographic projections, the meridians, which are great circles, appear as straight lines. On the skew Mercators, with the exception of the meridian through the vertex (oblique Mercator) and the central meridian, anti-meridian and meridians at 90º (transverse Mercator), the meridians appear as curves (although the curvature is small in the best areas of cover). With some exceptions, it is fair to say that the greater the departure from the point or line of origin of the chart, the more the straight line departs from representing a great circle; the longer the straight line the greater this discrepancy.

5. **Area of Operation**. The various chart projections have been devised to provide the most accurate representation of the Earth within limited areas. It is possible to represent the hemisphere accurately using five projections. If this plan were rigidly adhered to, the divergence (Δ) between the great circle and the straight line over distances of 500 nm and less would be very small. However, conditions may result in projections being used outside of the optimum areas and for this reason it is necessary to study the methods of plotting visual and radio position lines.

The Angular Divergence (Δ) Between the Straight Line and Great Circle

6. A general expression for the magnitude of Δ is given by:

$$\Delta = \tfrac{1}{2} \text{ ch long } (\sin \text{ mean lat} - n)$$

Ch long and mean lat refer to the change of longitude and latitude between the DR position and the bearing source; n is the constant of the cone which is treated in Volume 9, Chapter 3. For the purposes of this chapter it is sufficient to know that:

a. On the Mercator and skew Mercator projections, n = 0.

b. On the Lambert's conformal projection n may lie between 1 and 0, the precise value being a function of the parallel of origin. The GNC and JNC series of charts which are based on this projection, covering the latitude bands (approximately) of 0º to 40º and 32º to 76º, have values of n of 0.3118 and 0.785 respectively.

c. On the polar stereographic projection, n = 1.

7. **General Conclusions**. Assuming a small change of longitude along the bearing, the following deductions for each projection, based on the information above, can be made:

a. **Mercator**. At low latitudes, since the sine of a small angle is small and n = 0, Δ is small.

b. **Lambert's Conformal**. n is of the same order as the sine of the latitude for temperate latitudes, thus Δ is generally small in these areas. However, at the limits of a Lambert's projection there can be a considerable difference in the sine of the mean latitude and n, depending on the standard parallels selected and therefore the parallel of origin, where n = sin lat and divergence is nil.

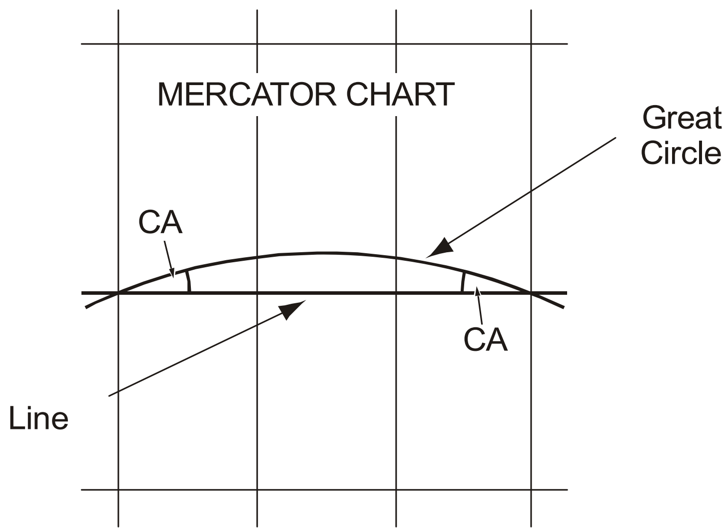
c. **Polar Stereographic**. In high latitudes, the sine of the mean latitude approaches 1, thus on a polar stereographic projection where n = 1, Δ is small.

PLOTTING PRACTICE WHEN BEARINGS ARE MEASURED AT A GROUND STATION

Mercator Projection

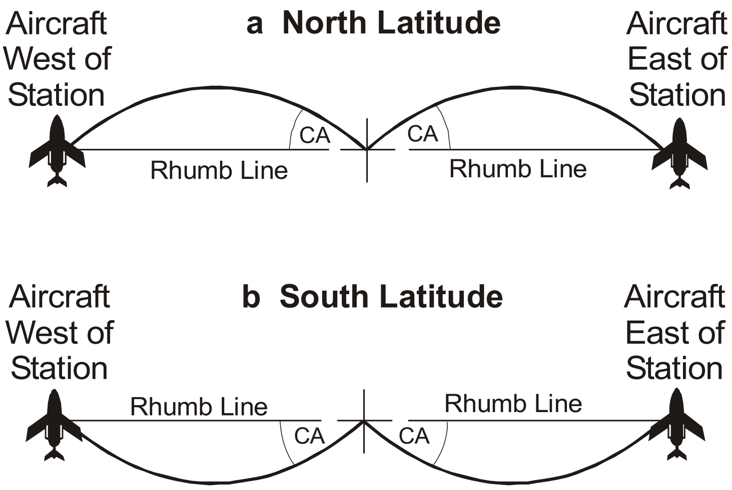
8. On a Mercator chart the straight line represents the rhumb line, while the great circle appears as a curve concave to the equator and, particularly outside of the Mercator's optimum latitude band of 12.5º S to 12.5º N, this difference must be considered when plotting bearings. The angle between the great circle and the rhumb line bearing between two points is known as conversion angle (CA, see Fig 1).

9-7 Fig 1 Great Circle and Rhumb Line on a Mercator Chart



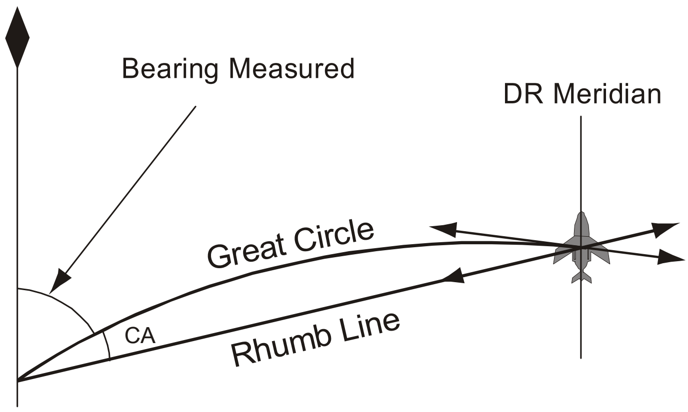
9. Although it is the great circle bearing which is measured by the direction finding equipment, it is the rhumb line bearing which is initially plotted since this is a straight line. This bearing is obtained by applying CA to the great circle bearing such that, in the northern hemisphere, the rhumb line lies nearer 180º T. In the southern hemisphere the CA is applied in the opposite sense, so that the rhumb line lies nearer 000º T (see Fig 2). For example, if in the northern hemisphere a true bearing of the aircraft is measured as 070º T and the conversion angle is 2º, the rhumb line bearing is 072º T.

9-7 Fig 2 Conversion of a Great Circle Bearing to the Corresponding Rhumb Line



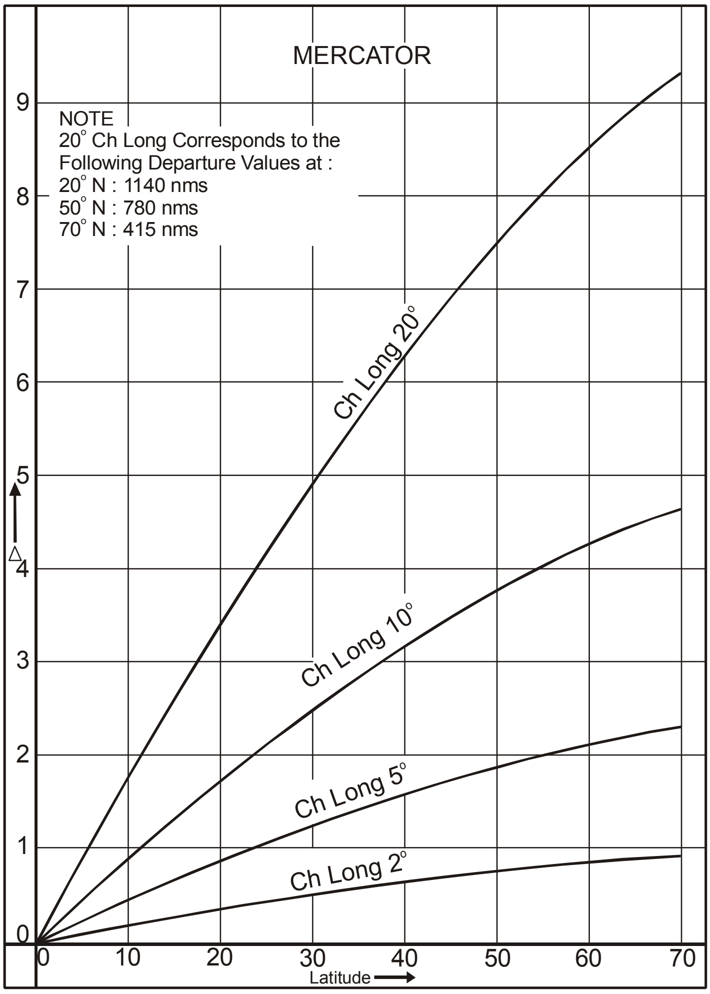
10. From Fig 3 it can be seen that, to plot the portion of the great circle bearing in the vicinity of the DR position, in this case, the rhumb line bearing should now be turned towards 180º T (in the northern hemisphere) at the DR meridian, through an angle equal to CA. In practice the value of the conversion angle would have to be quite large before there was any appreciable difference between the rhumb line and the great circle in the vicinity of the DR meridian, and the rotation of the rhumb line to lie along the great circle at the DR meridian can usually be ignored.

9-7 Fig 3 Plotting the Great Circle Position Line



11. **Calculation of Conversion Angle**. Conversion angle can be deduced from a graph (Fig 4), a nomogram (Fig 5), or from the formula which, since n = 0, reduces to CA = ½ ch long × sin mean lat. For practical purposes ½ × sin mean lat, which is called the conversion angle factor, can be reduced to six values to cover the hemisphere as shown in Table 1. CA is then the product of ch long and the conversion angle factor.

9-7 Fig 4 Conversion Angle Graph



9-7 Fig 5 Conversion Angle Nomogram

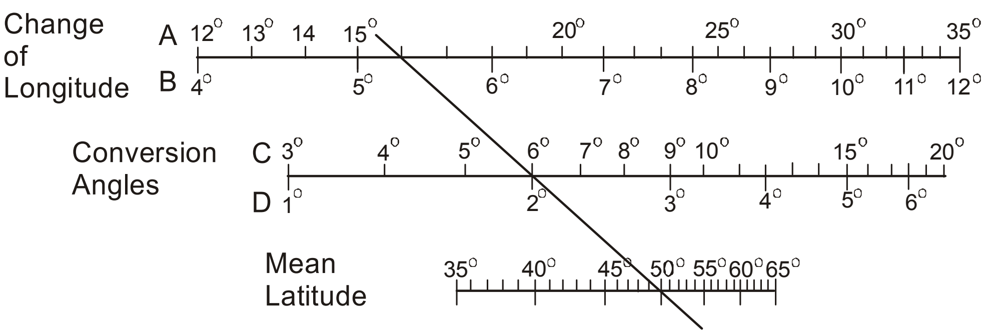


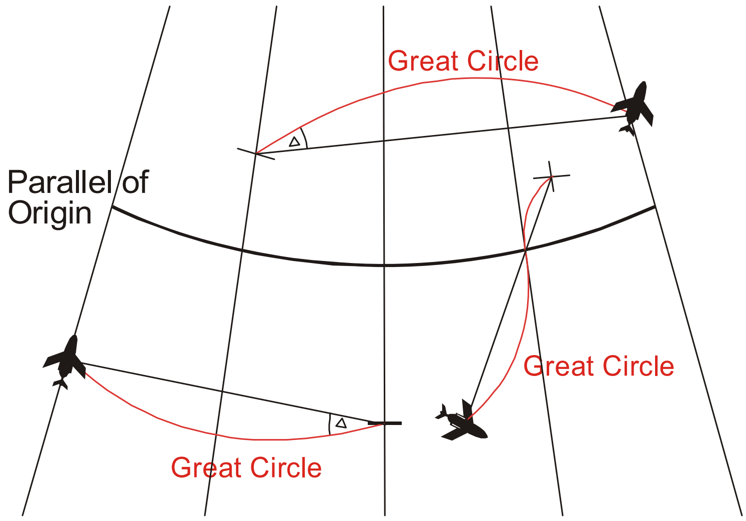
Table 1 Conversion Angle Factor – Mercator

Mean Lat	Conversion Angle Factor
0	
	0.0
6	
	0.1
18	
	0.2
30	
	0.3
45	
	0.4
65	
	0.5
90	

Lambert's Conformal Projection

12. Depending on the relative magnitude of the sine of the mean latitude and n, Δ may be positive or negative. The area of operation on a particular Lambert's projection will determine on which side of the straight line the great circle lies. If the mean latitude is greater than that of the parallel of origin, then the great circle will be closer to the pole than the straight line, and vice versa (see Fig 6). It should be remembered that the straight line on a Lambert's projection is not a rhumb line.

9-7 Fig 6 The Great Circle and the Straight Line on a Lambert's Conformal Projection

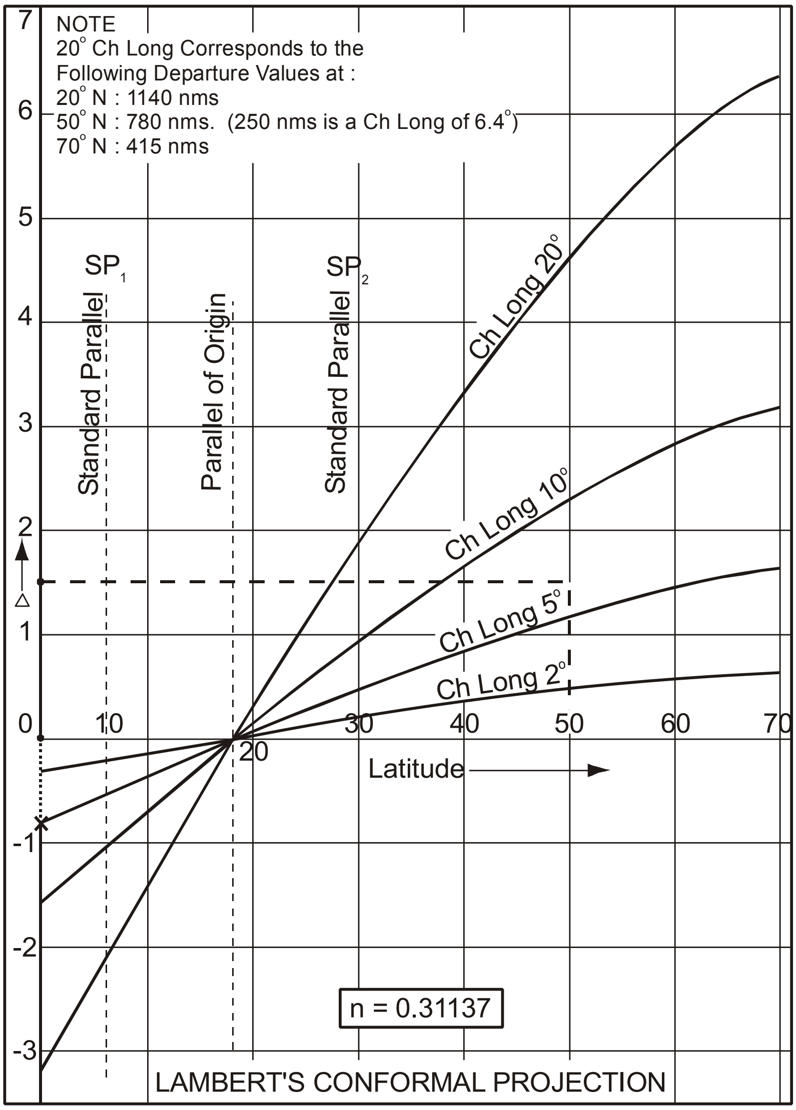


13. Theoretically, the problems of plotting a great circle on a Lambert's projection are essentially the same as those for the Mercator. The great circle is converted to the straight line equivalent by applying Δ, and this line is then rotated at the DR meridian through an angle Δ to give the tangent to the great circle. The application of Δ, in both cases, is such as to make the bearings nearer 180º if the mean latitude is greater than the parallel of origin, and nearer 000º if less than this parallel.

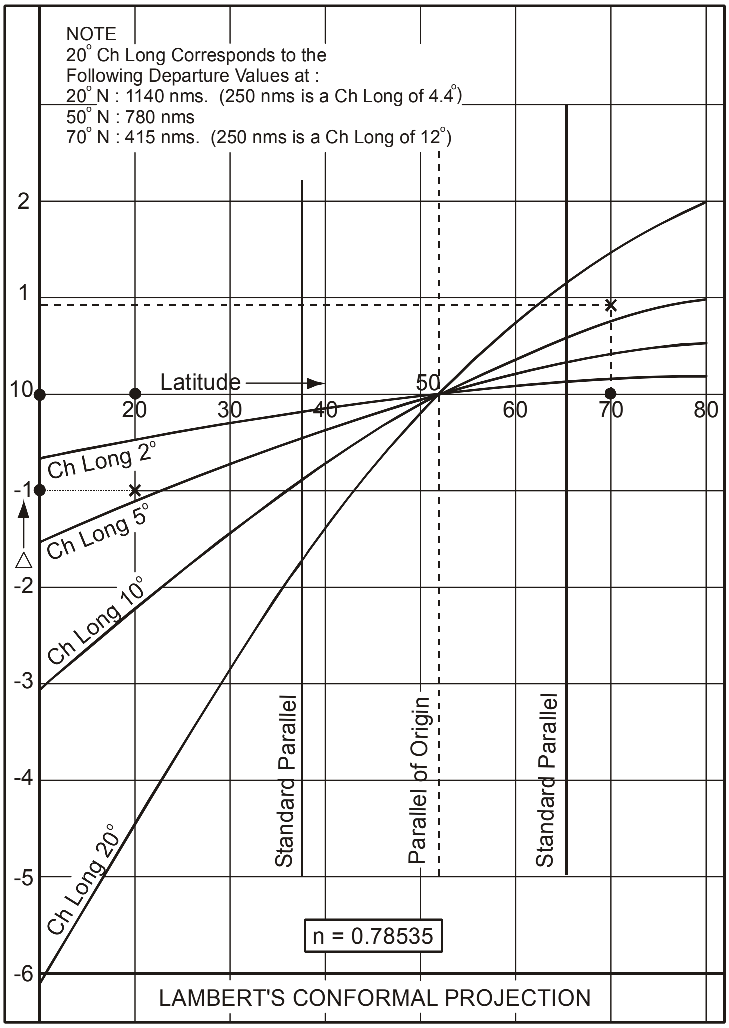
14. Graphs of mean latitude against Δ are shown at Figs 7 and 8 for values of n of 0.31137 and 0.78535 respectively. For a radio position line obtained over a range of 250 nm, Δ varies from

(approx) −0.6º to +1.5º in Fig 7 (at latitudes 0º and 50º), and from −1º to +1º in Fig 8 (at latitudes 20º and 70º). These are the maximum values in the circumstances as it is assumed that the aircraft and station are at the same latitude. If they were at any other position the ch long would be smaller over the given distance. Thus in the majority of circumstances the great circle can be plotted directly as a straight line with only minimal error.

9-7 Fig 7 Graph of Δ Against Mean Latitude (n = 0.31137)



9-7 Fig 8 Graph of Δ Against Mean Latitude (n = 0.78535)

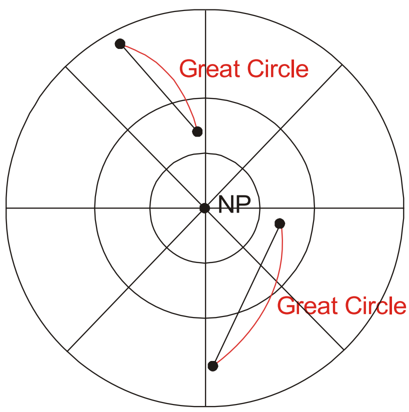


Polar Stereographic Projection

15. On the polar stereographic projection the great circle lies nearer the equator than does the straight line (see Fig 9), i.e. Δ is negative.

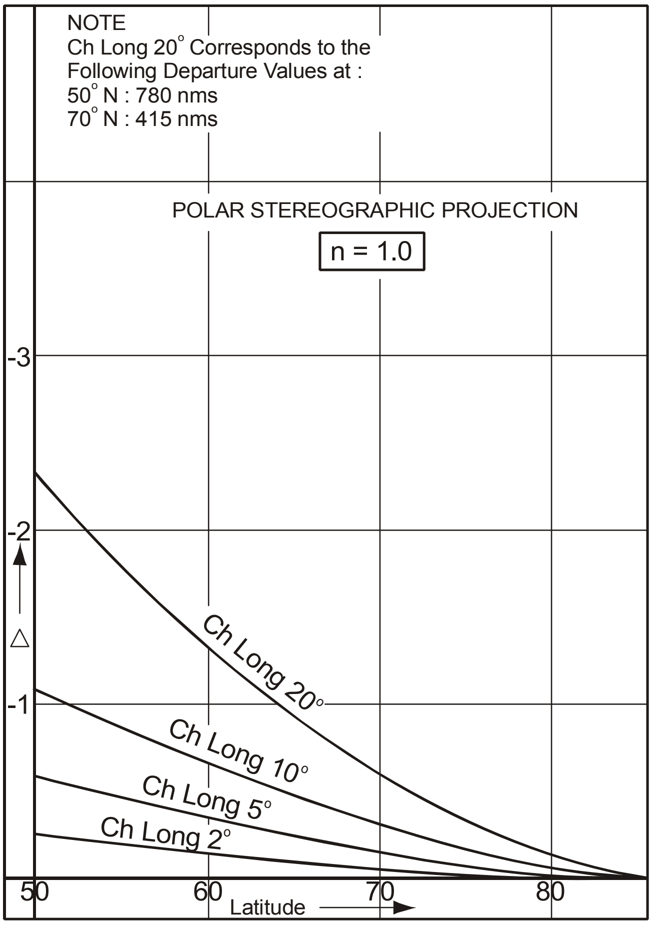
16. Although the procedure for plotting the great circle bearing is similar to that outlined for the Mercator and Lambert's projections, in practice, the value of Δ is so small that for all practical purposes in Polar Regions the great circle and straight line can be regarded as coincident.

9-7 Fig 9 The Great Circle and Straight Line on a Polar Stereographic Projection



17. A graph of Δ against mean latitude is plotted for various values of ch long at Fig 10. In the lower latitudes, at the extremes of the projection's useful cover, Δ can become significant and in this situation the conversion of the great circle to the equivalent straight line becomes necessary.

9-7 Fig 10 Graph of Δ for the Polar Stereographic Projection



Skew (Oblique and Transverse) Mercator Projections

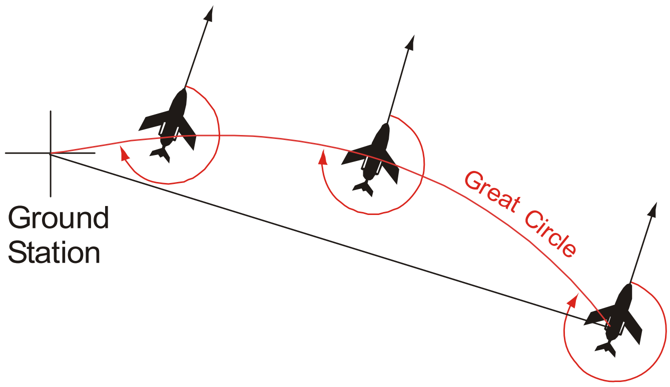
18. Divergence on skew Mercator charts causes the great circle to be concave to the false equator/central meridian. For a 250 nm long line, divergence is unlikely to exceed 0.5º on the oblique Mercator and 1.2º on the transverse Mercator. For both charts, if the bearing is measured at the ground station, the bearing is plotted from the meridian through the ground station.

PLOTTING PRACTICE WHEN BEARINGS ARE MEASURED AT THE AIRCRAFT

Introduction

19. The bearing measured at a ground D/F station will be the same for all aircraft transmitting from positions on the same great circle; consequently that great circle is the position line. The converse is not true; aircraft flying the same heading and lying on the same great circle through the station will not measure the same relative bearing from the ground beacon's transmission (Fig 11). Thus, where the bearing is measured at the aircraft, the great circle is not the position line. However, in most circumstances the difference is not significant. This outcome is the result of meridian convergence on the Earth and is not a function of any particular map projection.

9-7 Fig 11 Relative Bearings



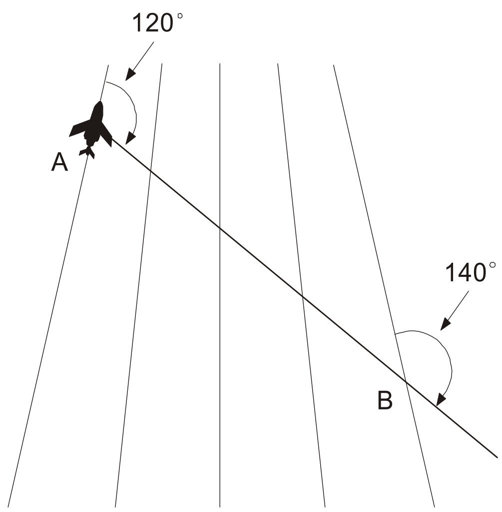
Plotting Relative Bearings on the Mercator Projection

20. Having measured the true bearing of the great circle between the aircraft and the station (i.e. relative bearing + true heading), the corresponding rhumb line can be obtained by applying conversion angle to the great circle such that, in the northern hemisphere, the rhumb line lies closer to 180º. The reciprocal is then plotted from the station. It should be emphasized that CA is applied to the true bearing of the great circle and not to the relative bearing. Rotation of the rhumb line at the DR meridian to account for meridian convergence is usually ignored in practice, bearing in mind the range of MF beacons and the latitude band in which the Mercator projection is used.

Plotting Relative Bearings on the Lambert's Conformal Projection

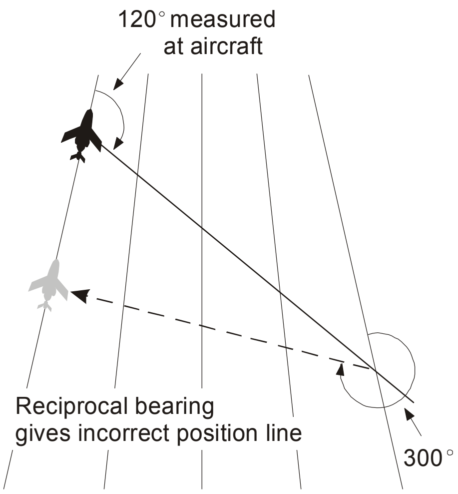
21. The effect of meridian convergence is very apparent on the Lambert's conformal projection. From Fig 12 it can be seen that the bearing of the great circle at A differs from that at B, the difference being Earth convergence.

9-7 Fig 12 The Effect of Convergence



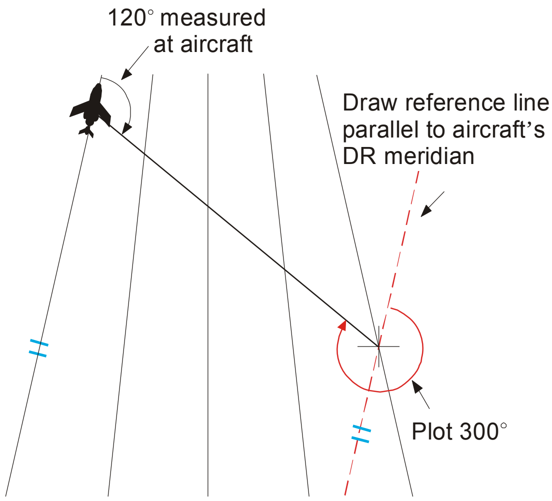
22. In attempting to plot the great circle bearing measured at the aircraft (eg relative bearings such as ADF or radar azimuth), it would be wrong merely to plot the reciprocal from the source. If this were done the bearing plotted would not cut the DR meridian at the measured angle (see Fig 13) but at the measured angle ± convergence.

9-7 Fig 13 Reciprocal Bearing (not allowing for Convergence)



This problem is overcome by plotting the reciprocal from the source with reference to a line parallel to the DR meridian (Fig 14).

9-7 Fig 14 Reciprocal Bearing (corrected for Convergence)



As with the Mercator chart, over the distances travelled by UHF, VHF, and MF radio waves, rotation of the position line at the DR meridian is normally unnecessary.

Plotting Relative Bearings on the Oblique Mercator Projection

23. The procedure for plotting on the oblique Mercator is the same as that used on the Lambert's conformal, ie the DR meridian is paralleled through the beacon (see Fig 14).

Plotting Relative Bearings on Polar Charts

24. The polar stereographic and polar transverse Mercator charts are invariably used with a grid overlay and used with grid navigation techniques. The plotting procedure for a relative bearing obtained while using a grid technique is very simple. Relative bearing + grid heading gives the required grid bearing and the reciprocal is then plotted from the origin. This procedure applies equally to Lambert's charts if a grid technique is being used.

SUMMARY

General

25. The methods used to plot position lines are a compromise between precision and expeditious plotting; the speedier and simpler approximation is normally to be preferred. Although it is not possible to state an invariable rule, consideration should usually be given to converting the great circle bearing to the straight line equivalent, whereas the need to rotate the position line at the DR meridian is normally ignored. The characteristics of the various common projections are summarized below.

26. **The Mercator**. The divergence between the straight line and the great circle varies directly as the sine of the mean latitude along the great circle. Since this projection is often used over a wide latitude band, significant values of Δ may be encountered. The need to calculate the straight line equivalent therefore often arises on the Mercator chart.

27. **The Skew Mercator**. Provided the skew Mercator is restricted to the optimum band of cover, i.e. ± 8º of false latitude, the values of Δ are small. If the chart is not gridded, then relative bearings must be plotted with reference to the DR meridian and not the meridian through the ground station.

28. **The Lambert's Conformal Projection**. The standard parallels on these charts can be widely spaced. Consequently, at the limits of cover, Δ can be significant. Thus, although the great circle and the straight line can be considered coincident over the greater part of the projection, this should not be assumed near the limits of cover. When plotting relative bearings, an allowance for convergence must be made, most simply by paralleling the DR meridian through the ground station.

29. **The Stereographic Projection**. Values of Δ on the stereographic projection are very small and, over the distances that bearings are taken, the straight line and great circle may be considered coincident.

30. **VOR and TACAN Bearings**. Although VOR and TACAN bearings are intercepted at the aircraft, the bearing information is encoded at the ground station. On all charts, TACAN and VOR radials should be plotted as originating from the appropriate ground station, and orientated with reference to magnetic North at the beacon. Where necessary, divergence should be applied.

CHAPTER 8 - DEAD RECKONING COMPUTER, MARKS 4A AND 5A

Contents **Page**

Table of Figures

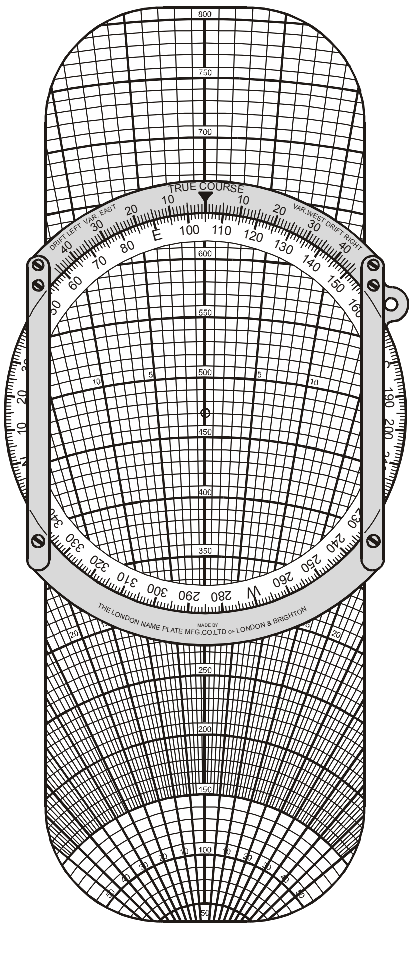
Introduction

1. The Dead Reckoning Computer (Mks 4A and 5A) is designed for solving the vector triangle problems of air navigation. The Mk 5A is a reduced size version of the 4A, produced for helicopter use. Both Mks include an airspeed computer and a circular slide rule.

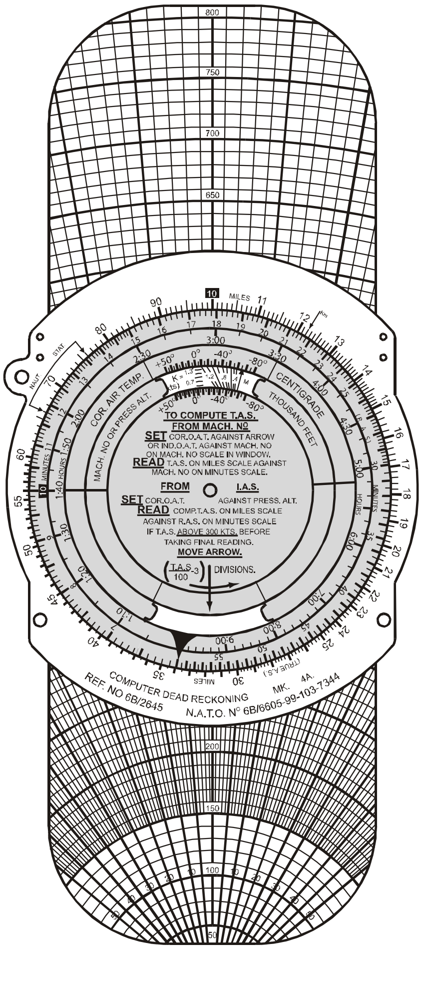
Description

2. The face and reverse of the Mk 4A computer are illustrated in Figs 1 and 2. The computer consists of a metal frame carrying, on one side, a transparent plotting disc in a graduated compass rose, and on the other, a circular slide rule which is also used for airspeed computation. A reversible sliding card printed with concentric speed arcs, radial drift lines, and a rectangular grid, moves under the plotting disc. One side of the sliding card is graduated from 50 to 800 speed units, while the other bears a range from 80 to 320 speed units together with a square grid graduated from 0 to 80. The units can represent whatever is required (e.g. kt, mph, kph), provided that the chosen unit is used consistently. Similarly, one side of the Mk 5A computer is graduated from 30 to 200 speed units and carries a square grid graduated from 0 to 100, while the other side is blank (but older versions may bear graduations from 20 to 120 and markings for helicopter jump navigation once used with the Wessex 1). The examples in this Chapter use the Mk 4A version.

9-8 Fig 1 DR Computer, Mk 4A – Face



9-8 Fig 2 DR Computer, Mk 4A - Reverse



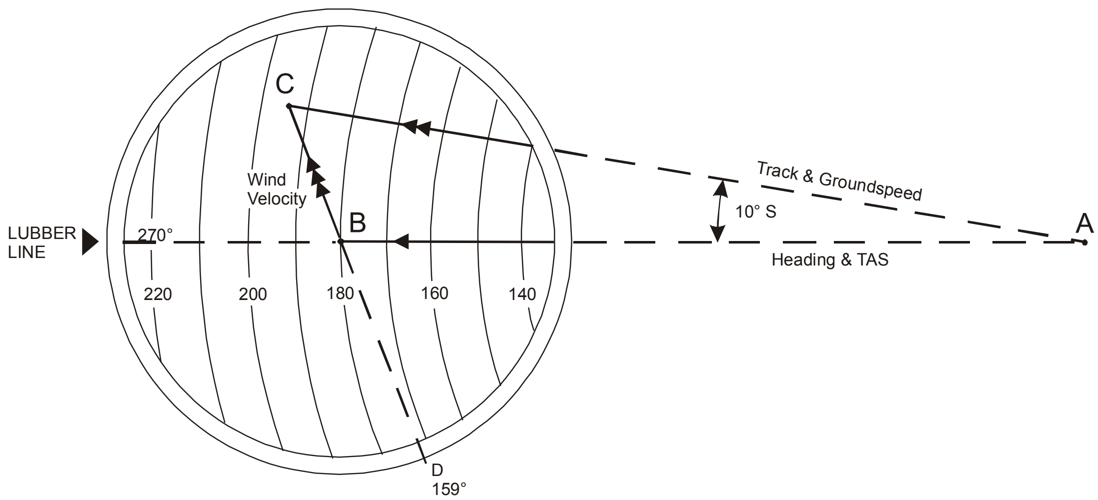
VECTOR TRIANGLE SOLUTION

Principle

3. The DR Computer reproduces, within the rotatable compass rose, that part of the triangle of velocities which is of prime concern, i.e. it shows the wind vector applied between the heading/true airspeed and the track/groundspeed vectors.

4. The principle is illustrated in Fig 3, in which ABC is the vector triangle. The compass rose (or bearing plate) is orientated to register the direction of the heading vector AB, i.e. 270° T, against a lubber line (marked TRUE COURSE on the computer). In doing this, the compass rose is orientated with respect to the other vectors. Thus, the wind vector BC is laid off down wind from B. The wind is therefore from D, i.e. 159° T. The direction of the track is shown as degrees to port or starboard of heading, e.g. in Fig 3 the drift is shown as 10° starboard which, when applied to heading, gives a track of 280° T. In Fig 3, if AB (airspeed) is 180 kt and BC (windspeed) 36 kt, then AC (groundspeed) is 196 kt.

9-8 Fig 3 Principle of DR Computer Mk 4A



5. It is unnecessary to have the whole of the vector triangle shown on the DR Computer. Therefore, only the essential part of the triangle, that containing the wind vector, is shown. The computer may be used over a range of speeds by adjusting the sliding card so that the curve corresponding to the true airspeed lies under the centre of the compass rose.

6. Thus, the transparent disc acts as a plotting dial on which only the wind vector is drawn, the heading vector being represented by the centre line on the sliding card and the track vector by the appropriate radial (drift) line. The centre of the disc is shown by a small circle which normally marks the end of the heading vector.

Operation

7. **Wind Speed and Direction**. To draw the wind vector when the speed and direction of the wind are given, the wind direction is set against the lubber line and the wind vector is drawn from the centre along the centre line in a direction away from the lubber line. The length of the line relative to the card scale represents the wind speed. The end of the vector so plotted is called the wind point. Conversely, if the

wind point has been found by other means, the wind speed and direction may be measured by rotating the plotting dial until the wind point lies on the centre line, on the opposite side of the centre circle to the lubber line. The wind direction is now read against the lubber line, while the distance of the wind point from the centre measured against the speed scale of the card gives the wind speed.

Note. The wind vector is always drawn away from the heading pointer because wind direction is conventionally quoted as the direction from which the wind is blowing. Headings and tracks are specified as the direction towards which the aircraft is going. It should be noted also that the scales on the two sides of the card are different so that a wind drawn using one scale must not be used with the other.

8. **Airspeed and Groundspeed**. Airspeed is always set, or read, on the centre line of the card under the centre of the plotting dial. Groundspeed is indicated by the speed circle under the wind point.

9. **Variation and Drift**. Although the plotting dial is normally orientated with respect to true north, a variation scale marked on either side of the lubber line can be used to convert true directions to magnetic and vice versa. This scale may also be used to obtain track by applying drift to heading, and vice versa.

Examples of Use

10. The examples which follow illustrate the versatility of the DR Computer in solving problems graphically, although only the first two are common in everyday practice. It should be remembered that, as noted in para 7, the wind always blows outwards from the centre of the computer. Animated diagrams are also provided to help explain the various calculations.

11. **To Find Track and Groundspeed (Fig 4)**. The problem is to find track and groundspeed, given:

Click here to view an animated diagram. (Fig 4)

Heading	-	185º T
TAS	-	420 kt
W/V	-	105°/39 kt

It is first necessary to ensure that the appropriate side of the sliding card is uppermost. The following steps are then carried out:

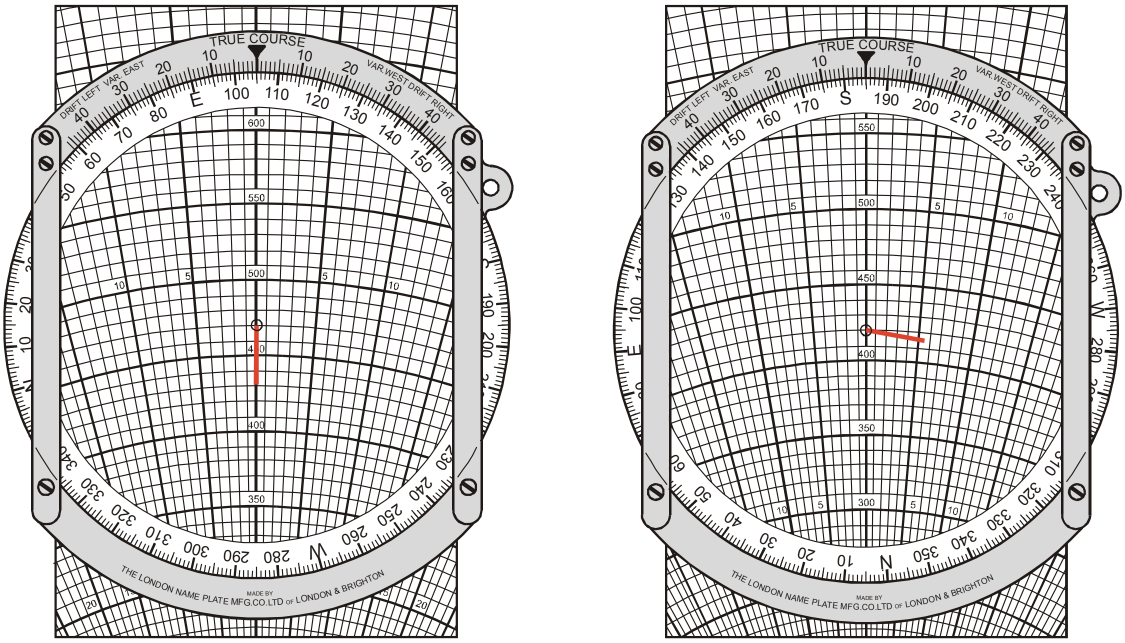
a. **Set the W/V**. The plotting dial is rotated until 105° on the compass rose is against the lubber line and a line is drawn from the centre of the plotting dial, away from the direction set, equal in length to 39 units on the scale (Fig 4a). Once familiarity with the use of the instrument has been gained, it will be found necessary only to plot the wind point, ie the end of the wind vector, rather than the complete line.

b. **Set Heading and TAS**. The plotting dial is rotated until 185° is against the lubber line, and the card is adjusted until the 420 speed arc lies under the centre of the plotting dial (Fig 4b).

c. **Read Off the Solution Under the Wind Point**. From Fig 4b, it will be seen that the wind point is on the 5° S drift line. Track can therefore be calculated as 185° T + 5° = 190° T, or it can be read off on the compass rose against the 5° mark on the drift scale. The groundspeed is given by the speed arc under the wind point, i.e. 415 kt.

9-8 Fig 4 Finding Track and Groundspeed

a Setting the W/V **b Reading the Solution**



12. **To Find Heading and Groundspeed (Fig 5)**. The problem is to find the heading and groundspeed, given:

Click here to view an animated diagram. (Fig 5)

Track Required	-	300º T
TAS	-	320 kt
W/V	-	195º/45 kt

It is first necessary to ensure that the appropriate side of the sliding card is uppermost. The following steps are then carried out:

a. Set the W/V. This is carried out in the manner described in para 11a.

b. Set TAS. TAS is set by adjusting the card until the 320 speed arc lies under the centre of the plotting dial.

c. The plotting dial is rotated until the required track is registered against the lubber line (Fig 5a). The drift indicated by the wind point (7½° S) is noted; this represents the drift that would be experienced if a heading of 300° T were steered.

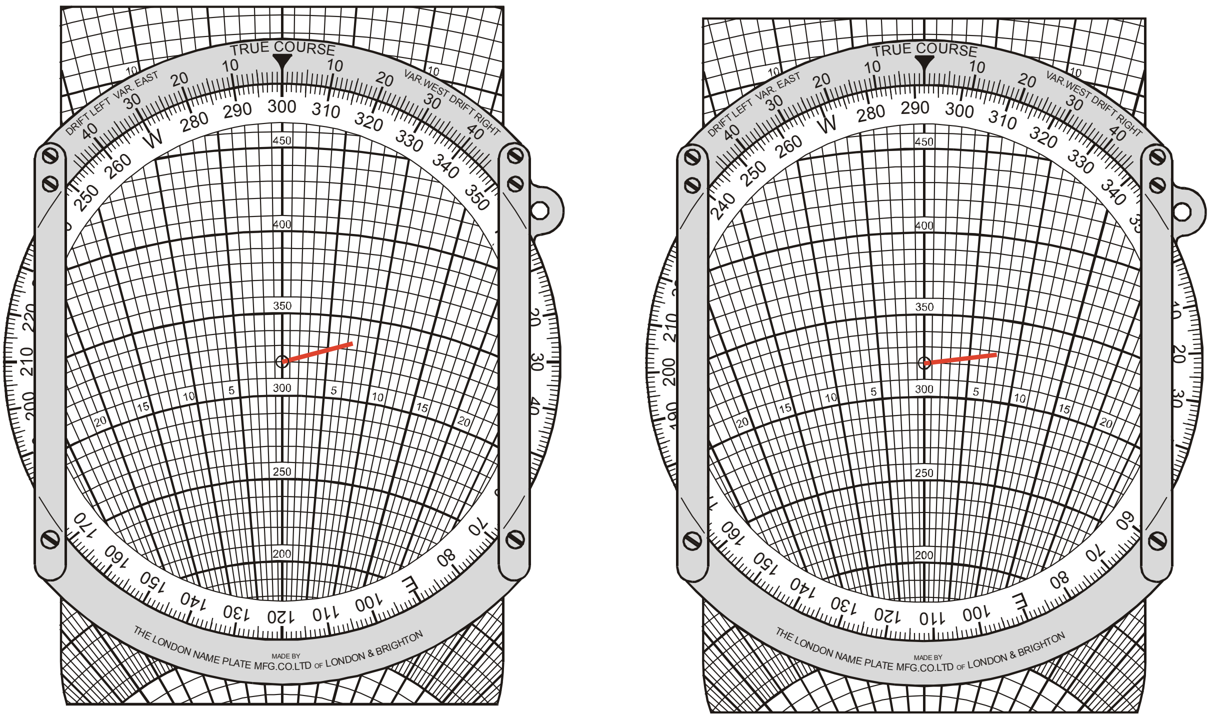
d. The required track is now set against the drift scale mark equivalent to the drift found in para 12c, i.e. 7½° S.

e. It is possible that the wind point will now indicate a slightly different drift value (Fig 5b). If this is the case, the plotting dial is adjusted until the required track is against this new value of drift on the drift scale; (8° S in this example).

f. The required heading (292° T) is read on the plotting dial against the lubber line, and the groundspeed (329 kt) is indicated by the speed arc lying under the wind point (Fig 5b).

9-8 Fig 5 Finding Heading and Groundspeed

a Setting Track and Reading Drift **b Setting Track against Drift Scale and Reading Solution**



13. **Finding W/V by the Track and Groundspeed Method (Fig 6)**. The problem is to find the W/V given the following data:

Click here to view an animated diagram. (Fig 6)

Heading	-	120º T
TAS	-	230 kt
Track Made Good	-	112º T
Groundspeed	-	242 kt

It is first necessary to ensure that the appropriate side of the sliding card is uppermost. The following steps are then carried out:

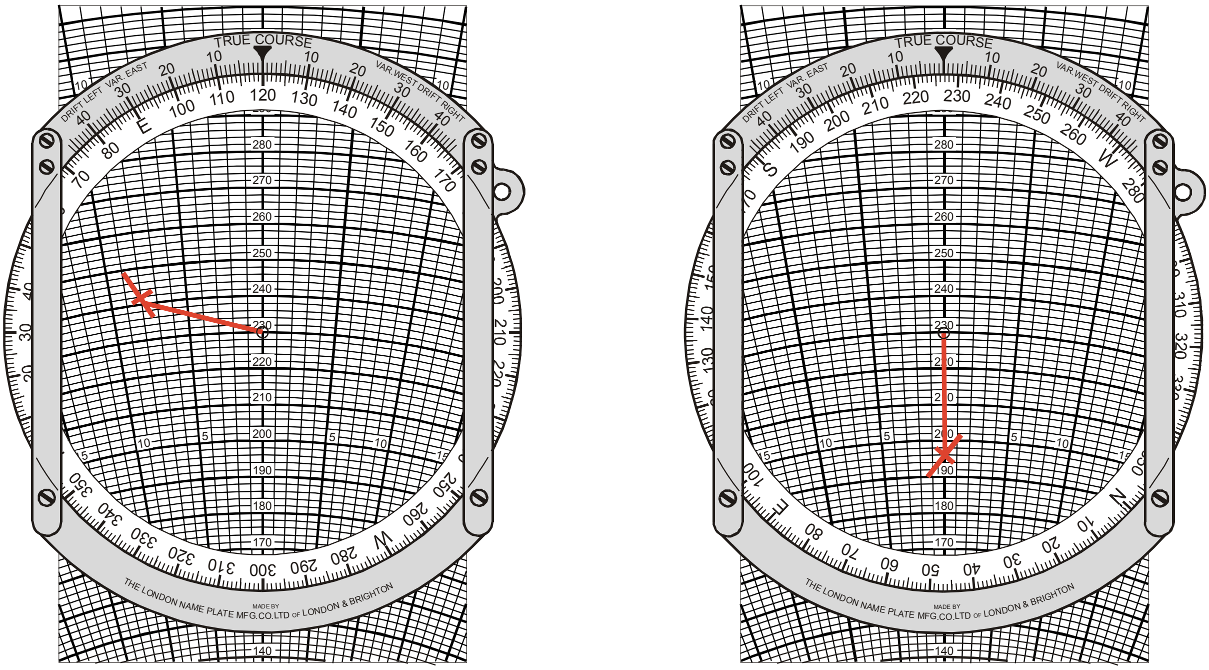
a. The heading and TAS are set as described in para 11b.

b. Set the Track Made Good and the Groundspeed. Firstly, the drift is calculated as the difference between heading and track, in this example 120° – 112° = 8° Port (P). A pencil mark is now made on the plotting dial (Fig 6a) where the drift line (8° P) intersects the speed arc representing the groundspeed (242 kt).

c. A line drawn from the centre of the dial to this point represents the wind vector. In order to measure it, the dial is rotated until the vector is aligned exactly with the centre line and running from the dial centre away from the lubber line (Fig 6b). The wind direction can now be read off against the lubber line (227º T), and the wind speed can be determined by measuring the length of the vector against the speed arcs (34 kt).

9-8 Fig 6 Finding W/V by Track and Groundspeed Method

a Plotting Drift and G/S and Drawing the Wind Vector | **b Reading the W/V**



14. **Correcting a W/V by Finding the Error in a DR Position (Fig 7)**. It is possible to find a new wind velocity by applying a correction vector to the wind velocity in use, given a simultaneous DR position and fix. As an example, suppose that the wind velocity that has been used is 345º/30 kt, and that, after 20 minutes of flight, the aircraft's position is fixed at a position which bears 220º T/5 nm from a DR position. The procedure is as follows:

Click here to view an animated diagram. (Fig 7)

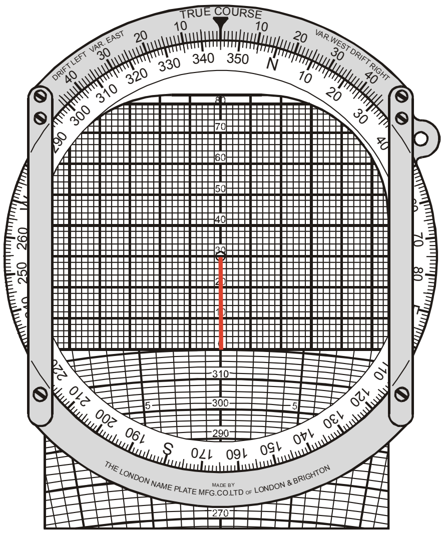
a. The card is adjusted until the square-ruled section is under the dial. The wind direction is set against the lubber line and the wind vector in use is drawn on the dial using a convenient scale, e.g. one large square = 10 nm (Fig 7a).

b. The error per hour is calculated (an error of 5 nm in 20 minutes is equivalent to 15 nm per hour). The dial is rotated until the bearing of the fix from the DR position is against the lubber line. A correction vector is then drawn from the end of the wind vector, parallel to the grid lines and towards the lubber line. The correction vector is of a length equal to the hourly error at the chosen scale (Fig 7b).

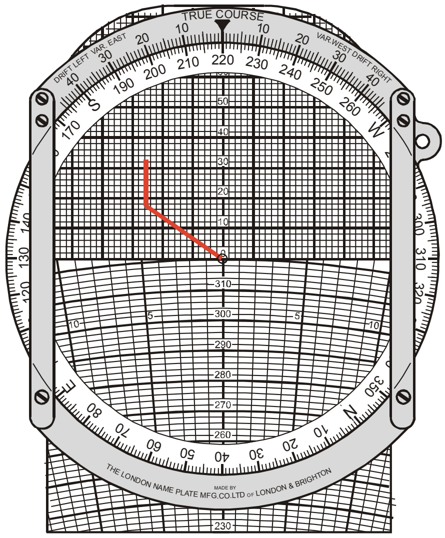
c. The line from the centre dot to the end of the correction vector represents the new wind vector. It can be measured by rotating the dial until the vector is aligned with the centre line and then reading the direction from the lubber line and measuring the speed against the chosen scale of the square ruled section of the card (Fig 7c). In the example, the new wind is 003º/40 kt.

9-8 Fig 7 Correcting a W/V

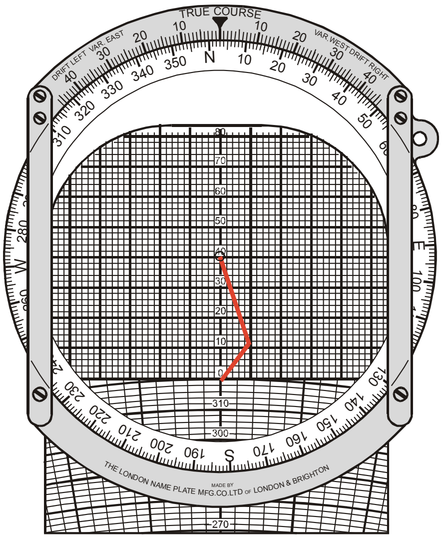
a Drawing the Wind Vector



b Drawing the Correction Vector



c Constructing a New Wind Vector and Reading the Solution



15. **Interception (Fig 8)**. Interception problems concerning a slow-moving target, such as a ship, can be solved satisfactorily on the DR computer. It is easier to deal with the problems in two steps. The first step is to find the relative wind velocity, while the second is to determine the heading to make good the relative track and the groundspeed along it, i.e. the speed of closing along the line of constant bearing. As an example, consider the following data:

Click here to view an animated diagram. (Fig 8)

W/V	-	060º /15 kt
TAS	-	140 kt
Ship's track	-	000º T
Ship's speed	-	25 kt

Ship's position from aircraft - 80 nm on a bearing of 330º T.

a. **To Find Relative W/V**.

(1) Adjust the card until the square-ruled part is under the dial.

(2) Set the W/V on the dial using any suitable scale (Fig 8a).

(3) Turn the dial until the ship's track (000º T) is registered against the lubber line.

(4) From the end of the wind vector, draw a line equal to the ship's speed to scale (25 kt) parallel with, but away from, the lubber line (Fig 8b). This is the vector of the ship's track and speed reversed.

(5) Join the centre of the plotting dial to the end of this second vector to obtain the vector of the relative W/V (Fig 8c). It measures 022º/35 kt.

b. **To Find Heading to Intercept and Speed of Closing**.

(1) Proceed as in para 11, to find the heading to steer and G/S to make good a track of 330º in a W/V of 022º/35 kt with a TAS of 140 kt.

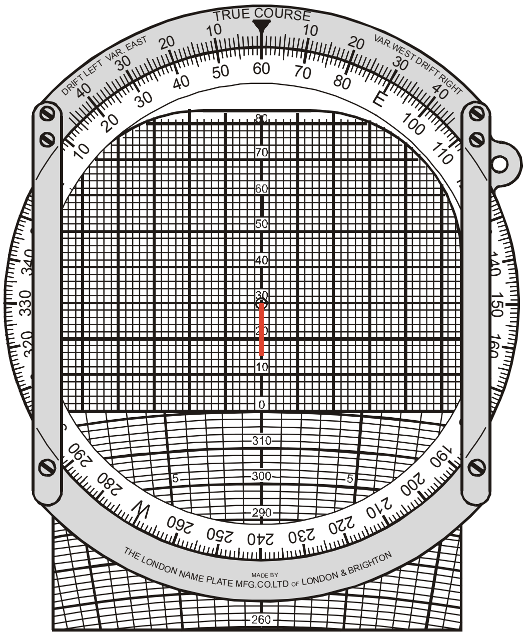
(2) The heading is found to be 341º T.

(3) Although a G/S of 117 kt is found, the figure actually represents the speed of closing along the relative track, or line of constant bearing. Thus, the ship will be intercepted after 41 minutes of flight.

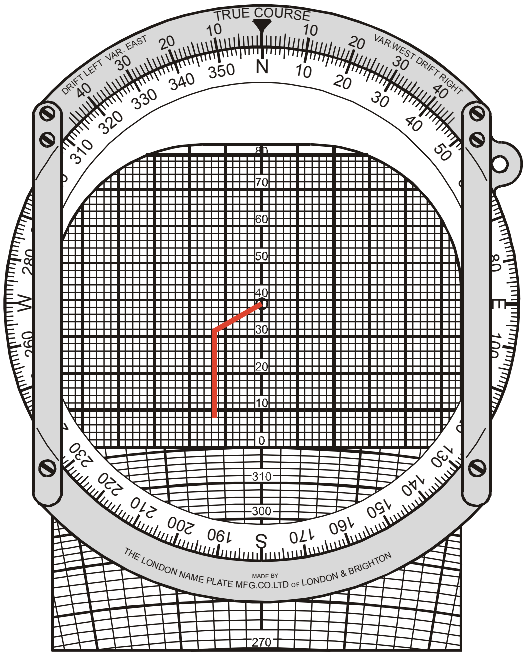
Note. If the relative W/V is found using the same basic scale as represented by the concentric arcs, there is no need to measure the relative W/V. The second step can then be taken immediately the first two vectors of the first step are drawn.

9-8 Fig 8 Interception

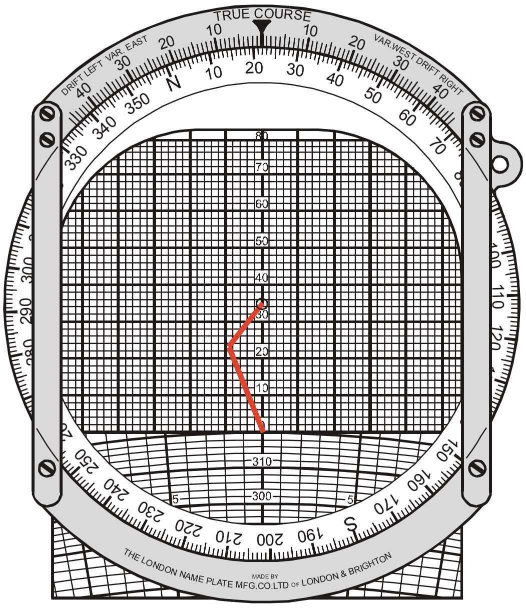
a Setting the W/V



b Setting Ship's Speed



c Drawing and Reading the Relative W/V



16. **To Calculate Convergence (Fig 9)**. Convergence may be determined using the following procedure:

Click here to view an animated diagram. (Fig 9)

a. Set the compass rose with North against the lubber line.

b. Set the zero point of the squared portion of the slide under the centre of the plotting disc.

c. Mark ch long upwards from the zero point, on the squared section, using any convenient scale (Fig 9a).

d. Rotate the compass rose to set Mean Lat against the lubber line (Fig 9b).

e. Measure convergence horizontally on the squared grid (Fig 9b).

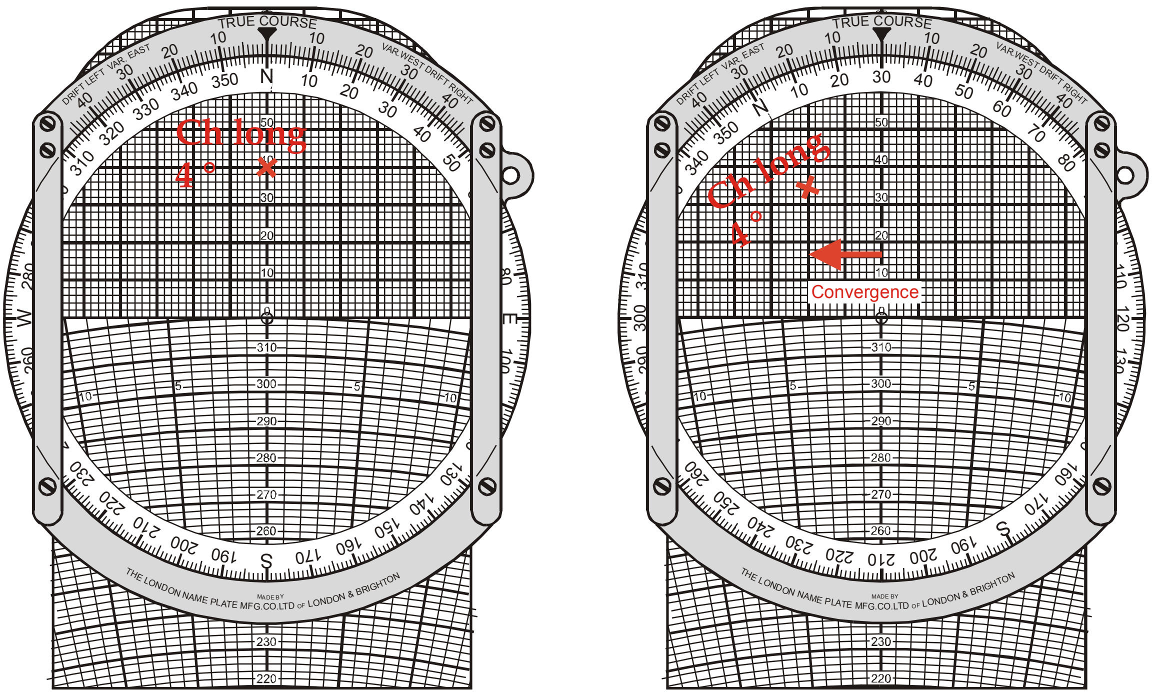
Example: Ch long 4º, Mean Lat 30º

Convergence = 2º

9-8 Fig 9 Calculating Convergence

a Marking Ch Long

b Setting Mean Latitude and Reading Convergence



AIRSPEED COMPUTER

Description

17. The airspeed computer works on the slide rule principle and has scales for the following applications:

a. Computation of TAS from CAS, corrected outside air temperature (OAT) and pressure altitude, with an ancillary scale to allow compressibility corrections to be made to TAS above 300 kt. (Note: CAS is annotated as RAS on inner scale.)

b. Inter-conversion of TAS and Mach Number.

c. Proportion problems.

Use for Airspeed Computations

18. The procedure for calculating TAS from inputs of CAS, corrected OAT, and pressure altitude is as follows:

a. The inner disc is rotated so that the value of corrected OAT is set against the value of altitude, in thousands of feet, in the window (Fig 10a).

b. The value of computed TAS can now be read on the outer scale against the value of CAS on the inner scale (Fig 10a).

c. If the computed TAS is above 300 kt, an additional correction must be made for compressibility error. The correction scale appears in the window, below the altitude window, and the correction is made by rotating the inner disc anti-clockwise so that the reading of the correction scale, against its index, is increased by the value of:

$$\frac{\text{Computed TAS}}{100} - 3 \text{ divisions}$$

d. The corrected TAS is now read off on the outer scale against the original CAS on the inner scale.

Note. To obtain the most accurate results from the computer, pressure altitude and corrected OAT should be used for all airspeed computations. Even so, when computing TAS for altitudes, particularly above 30,000 ft, noticeable, but navigationally insignificant, errors are produced when compared with results using the mathematical formula.

19. **Example**. As an example, consider the calculation of TAS from the following data:

Click here to view an animated diagram. (Fig 10)

Pressure Altitude	-	48,000 feet
Corrected OAT	-	– 56º C
CAS	-	210 kt

The procedure is as follows:

a. Set –56° against 48 in the altitude window (Fig 10a).

b. Against 210 on the inner scale, read the computed TAS on the outer scale - 500 kt (Fig 10a).

c. As the computed TAS exceeds 300 kt, a compressibility correction must be made. The current value of the correction scale is 25½. This must be adjusted by:

$$\frac{\text{Comp TAS}}{100} - 3 = \frac{500}{100} - 3 = 2 \text{ divisions}$$

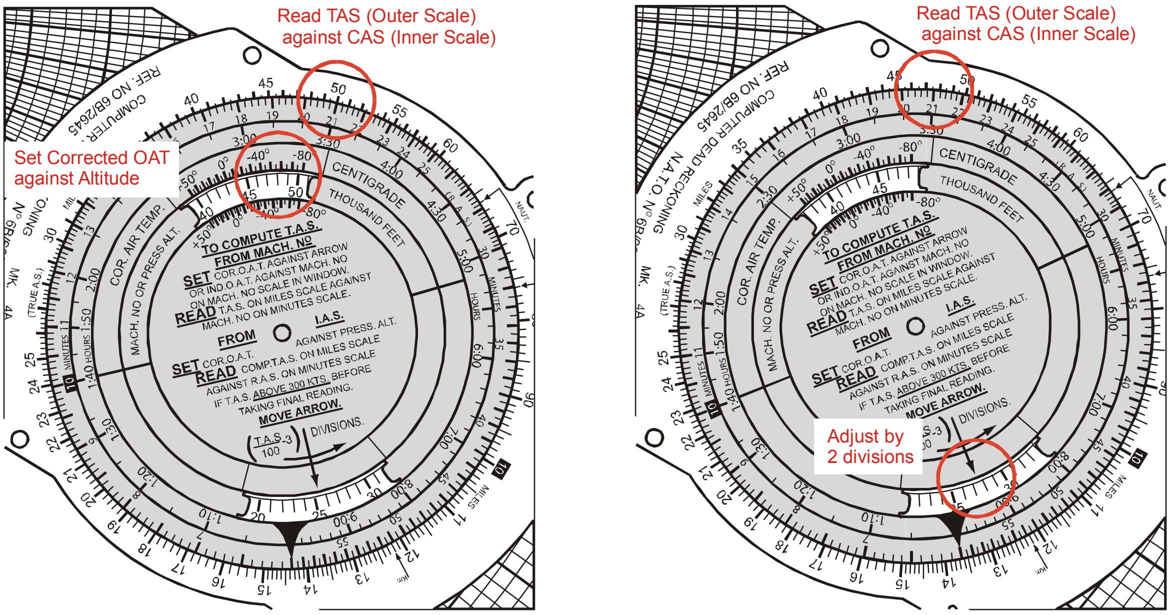
d. The correction scale is therefore made to read 27½ against its index (Fig 10b).

e. The corrected value of TAS is now read on the outer scale against the value of CAS (210) on the inner scale (Fig 10b). The result is 476 kt.

9-8 Fig 10 Calculating TAS

a Setting Altitude against OAT

b Applying Compressibility Correction and Reading the Solution

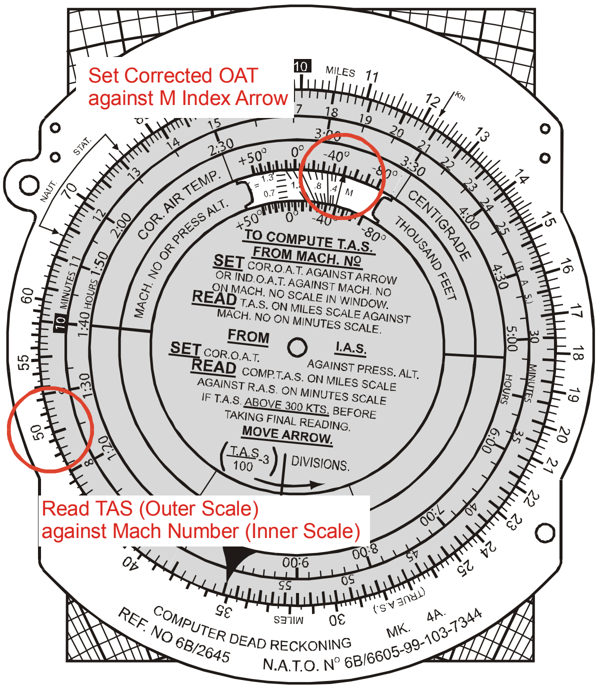


Mach Number/True Airspeed Conversion

20. The Mach number scale appears in the altitude window at the upper end of the altitude scale. The scale can be used for converting Mach number to TAS and vice versa (Fig 11).

Click here to view an animated diagram. (Fig 11)

9-8 Fig 11 Mach No/TAS Conversion



21. **Inter-conversion of Mach Number and TAS**. Mach number and TAS may be inter-converted in one of two ways:

a. Set corrected outside air temperature against the Mach index arrow (marked M).

b. Set indicated outside air temperature against the intersection of Mach number and 'K' factor. ('K' factor is empirically determined for each aircraft type).

In either case, TAS is read on the outer scale against Mach number on the inner scale.

22. **Example**. It is required to determine the TAS corresponding to M 0.85 in a corrected OAT of – 50° T.

Using the method in para 21a (see Fig 11):

a. Set –50° C against the 'M' index arrow.

b. Read TAS (495) kt on the outer scale against 0.85 on the inner scale.

CIRCULAR SLIDE RULE

Introduction

23. The reverse sides of the Mks 4A and 5A DR Computer carry a circular slide rule. Although the pocket electronic calculator has superseded the slide rule for carrying out arithmetic, the circular slide rule is nevertheless useful for the solution of the normal speed, distance and time, and fuel consumption problems which regularly occur in navigation. It should be remembered that, as with all slide rules, decimal points are ignored during calculation and only inserted at the end. It is therefore important to have an appreciation of the order of the result expected.

24. Reflecting the normal usage of the circular slide rule, the outer scale is marked 'MILES', and the scale on the rotating disc (the inner scale) is marked 'MINUTES'. The inner scale has a large black arrow indicating one hour.

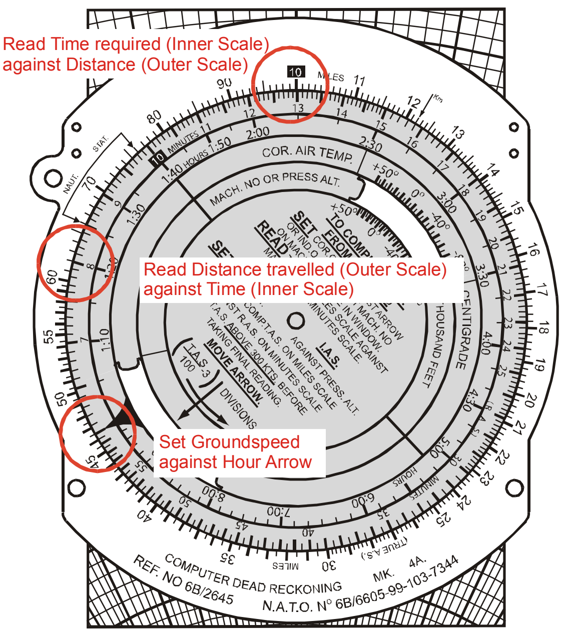
Calculating Distance and Time

25. The problem most often encountered, which is solved readily by the circular slide rule, is that of determining the time taken to cover a given distance, or conversely the distance covered in a given time. To solve these problems, the given groundspeed is set, in knots on the outer scale, against the black (hour) arrow of the inner scale. Distance is then read on the outer scale, against time in minutes on the inner scale.

26. **Example (Fig 12)**. Given a groundspeed of 470 kt, how long will it take to fly 100 nm, and how far will the aircraft fly in 8 minutes? By setting 47 on the outer scale against the hour arrow it will be seen that a time of 12.8 minutes on the inner scale will be read against the 10 mark on the outer scale, ie 100 nm takes 12.8 minutes; against 8 on the inner (minutes) scale, a distance of 62.5 nm will be read on the outer scale.

Click here to view an animated diagram. (Fig 12)

9-8 Fig 12 Distance/Time Calculation

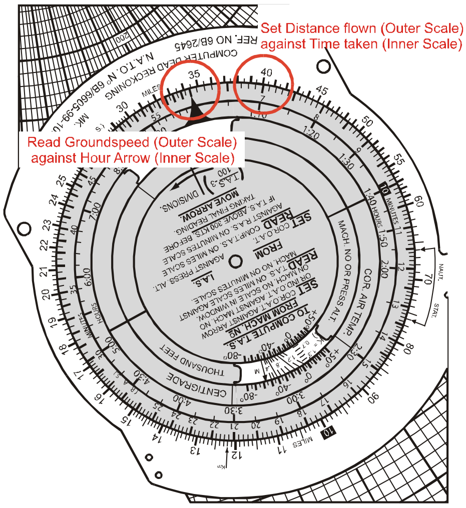


Calculating Groundspeed

27. If the distance flown in a given time is known, the circular slide rule can be used to find the groundspeed. The procedure is to set the distance flown on the outer scale against the time taken on the inner scale. The groundspeed is then read on the outer scale against the black (hour) arrow of the inner scale, e.g. if 40 nm are flown in 7 minutes, a groundspeed of 343 kt is read against the black arrow (Fig 13).

Click here to view an animated diagram. (Fig 13)

9-8 Fig 13 Calculating G/S

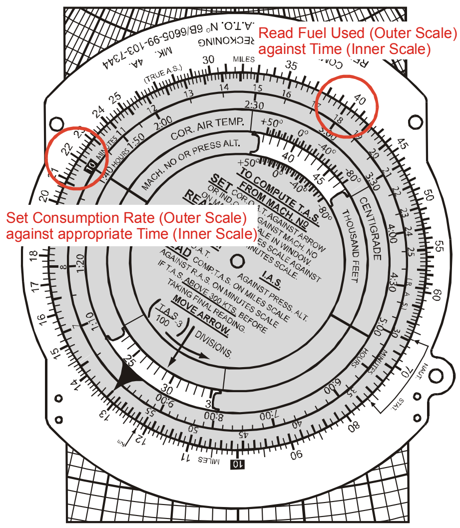


Fuel Consumption

28. Given the fuel consumption rate (e.g. in kg/min) and the leg time over which that consumption rate applies, the circular slide rule can conveniently be used to determine the total fuel used. The fuel consumption rate is set on the outer scale against the appropriate time on the inner scale. The total fuel used can then be read on the outer scale against the leg time on the inner scale. Thus, in the example, Fig 14, a fuel consumption rate of 22 kg/min is set against the 1 minute mark (remembering that there are no decimal points and 1 is identical to 10). Over a leg time of 18 minutes, it will be seen that 396 kg of fuel is used.

Click here to view an animated diagram. (Fig 14)

9-8 Fig 14 Fuel Consumption



Unit Conversions

29. Unit conversions only require the multiplication and division of numbers, so any such calculation could be carried out on a slide rule. However, this is not normally the quickest or most accurate method; electronic calculators or graphical methods are generally preferred. The circular slide rule can readily be used to convert between nautical miles, statute miles, and kilometres. The outer scale has indices marked for each unit and, by setting the known value on the inner scale against its respective index, the corresponding values in the other units can be read against the relevant index. Thus, for example, setting 18 against the 'Naut' index gives values of 20.7 statute miles and 33.3 kilometres (Fig 15).

Click here to view an animated diagram. (Fig 15)

9-8 Fig 15 Unit Conversion

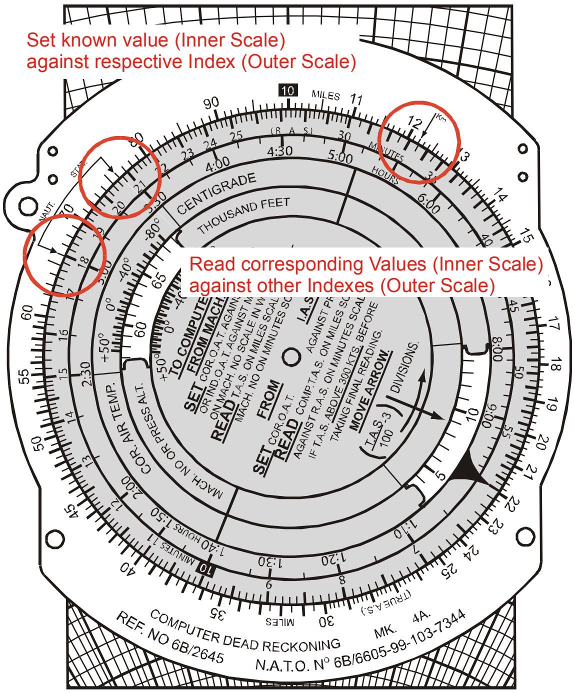


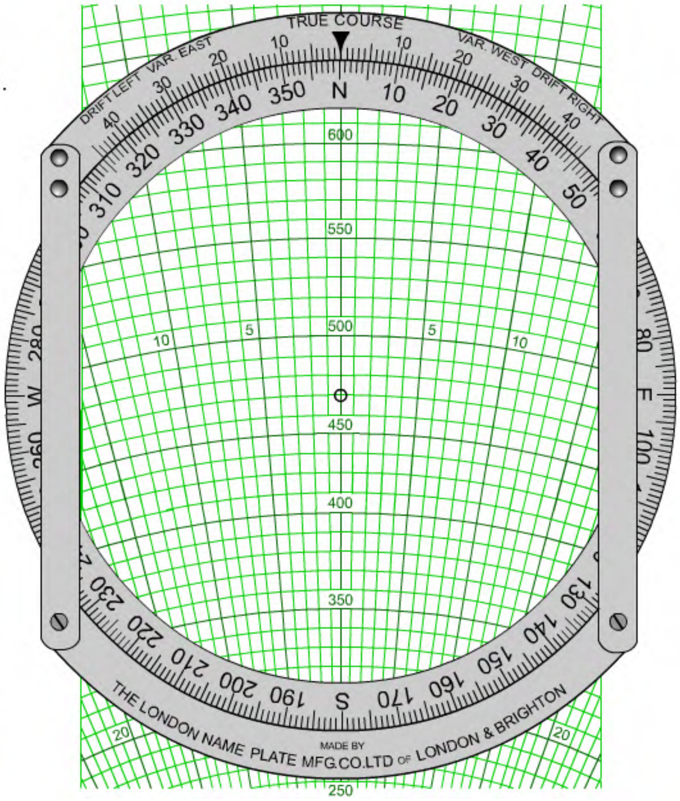
Fig 4 - Finding Track and Groundspeed (Return to text)

Problem:

To find Track and Groundspeed.

Given:

Heading	185°T
TAS	420 kt
W/V	105° / 39 kt



Continue

Fig 5 – Finding Heading and Groundspeed (Return to text)

Problem:

To find Heading and Groundspeed.

Given:

Track Required	300°T
TAS	320 kt
W/V	195° / 45 kt

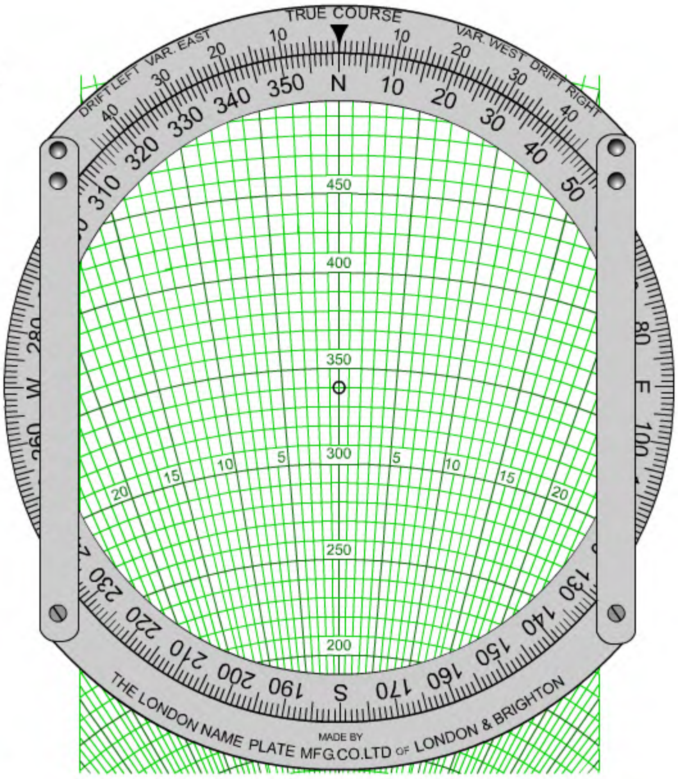


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Fig 6 – Finding W/V by Track and Groundspeed Method (Return to text)

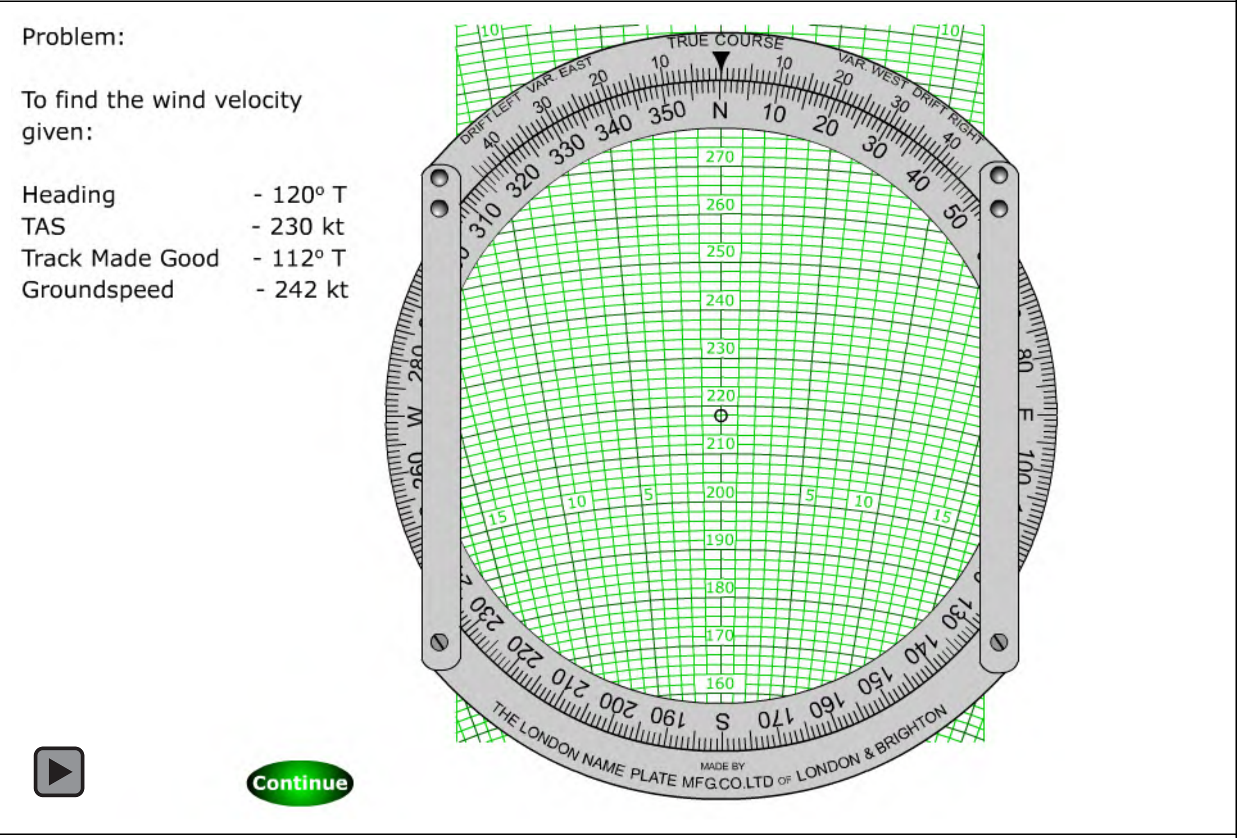

Fig 7 – Correcting a W/V (Return to text)

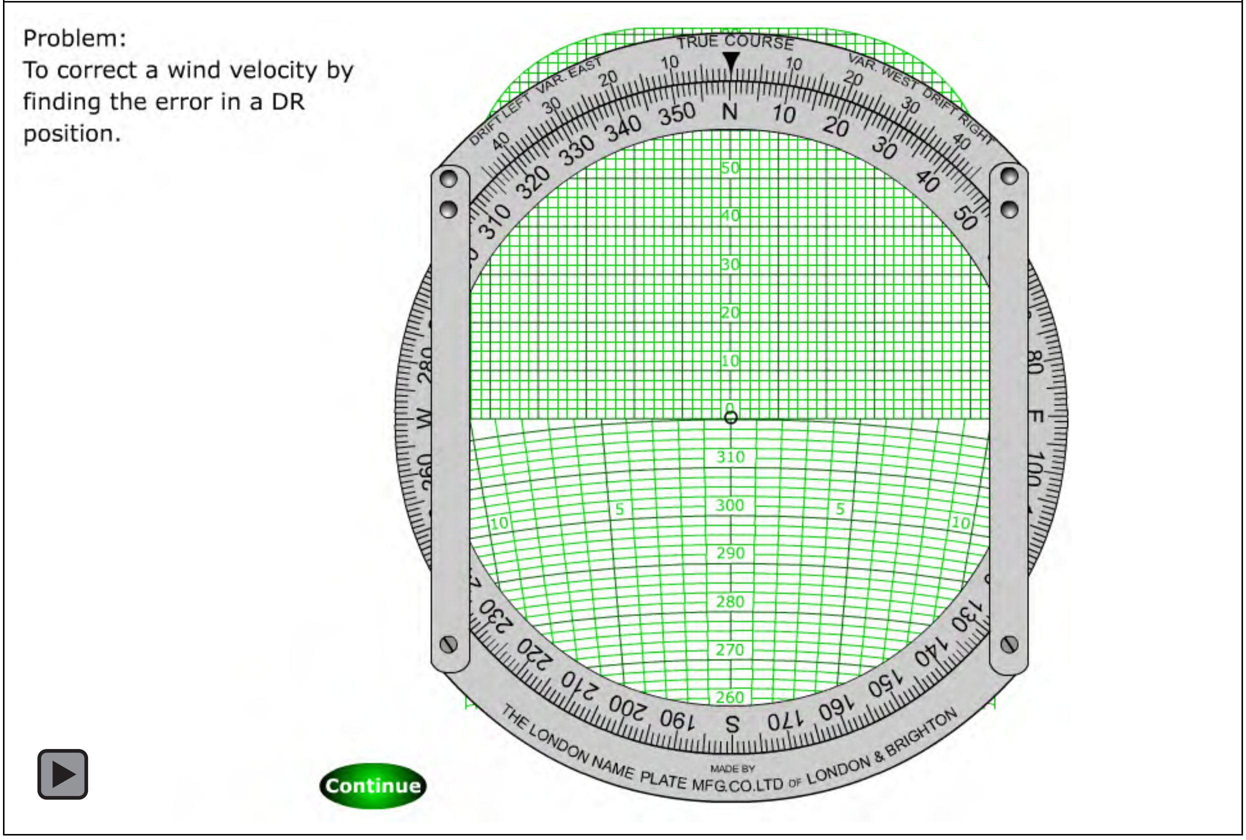

Fig 8 – Interception (Return to text)

Problem:
To determine the heading required to intercept a slow moving target, such as a ship.

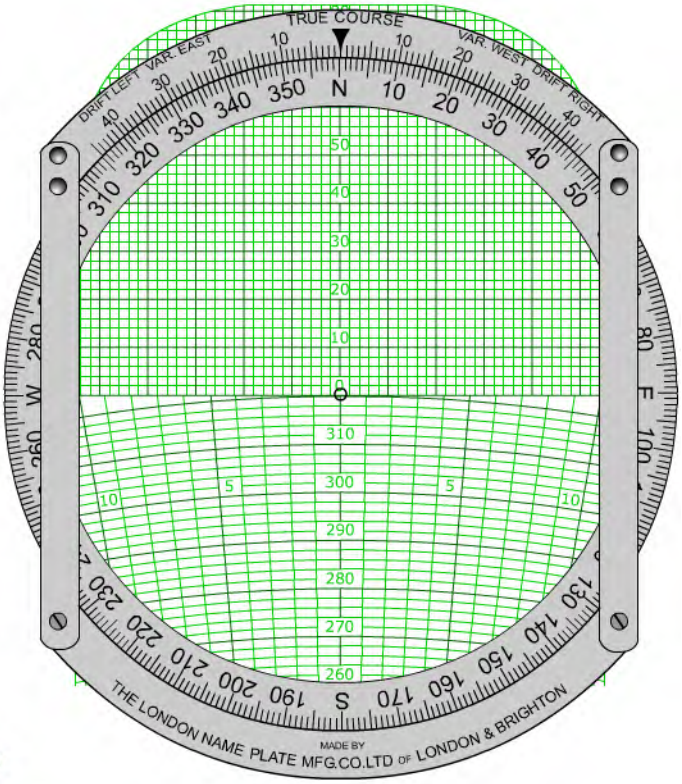

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Fig 9 – Calculating Convergence (Return to text)

Problem:

To determine convergence given that:
Ch long = 4°
Mean Lat = 30°

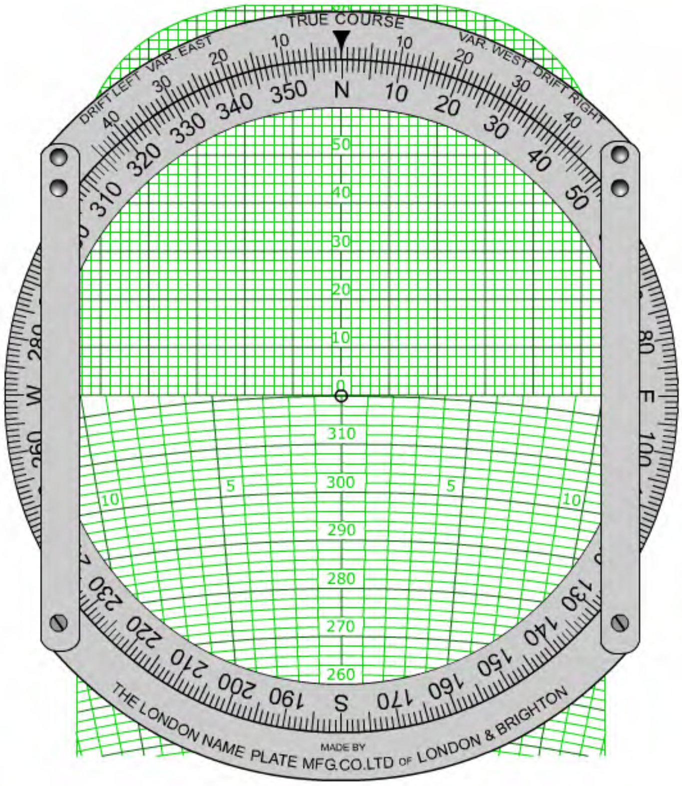

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Fig 10 – Calculating TAS (Return to text)

Problem:

To calculate TAS from the given data:

Pressure Altitude - 48000 ft

Corrected OAT - -56 ° C

CAS - 210 kt

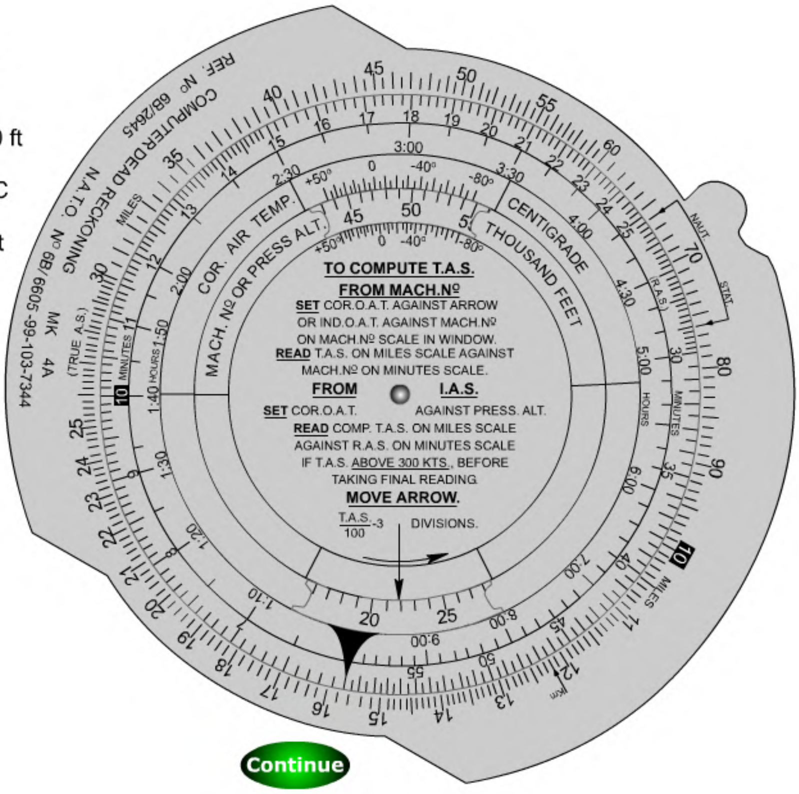

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Fig 11 – Mach No/TAS Conversion (Return to text)

Problem:

To calculate TAS from the given data:

Mach No - M 0.85

Corrected OAT - -50 ° C

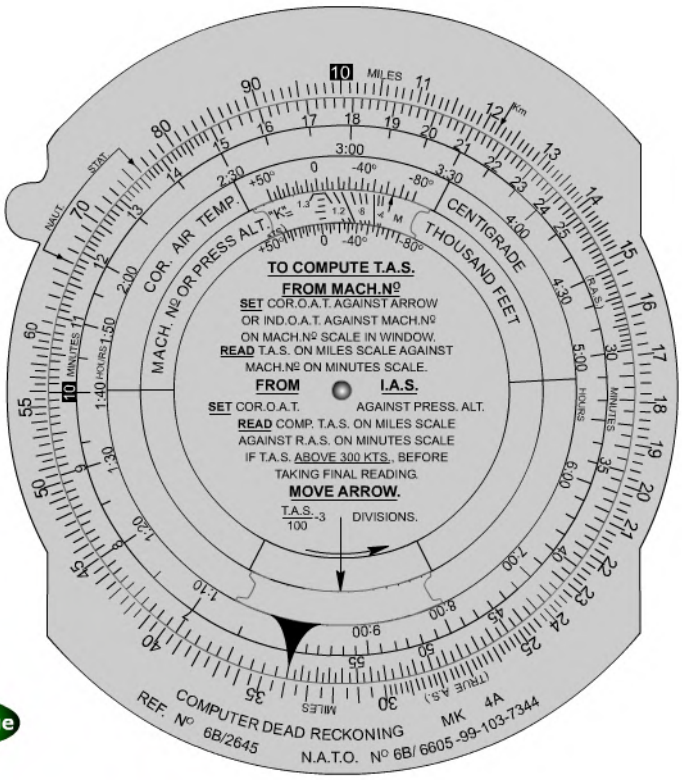

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Fig 12 – Distance/Time Calculation (Return to text)

Problem:

Given a groundspeed of 470 kt, how long will it take to fly 100 nm, and how far will the aircraft fly in 8 minutes?

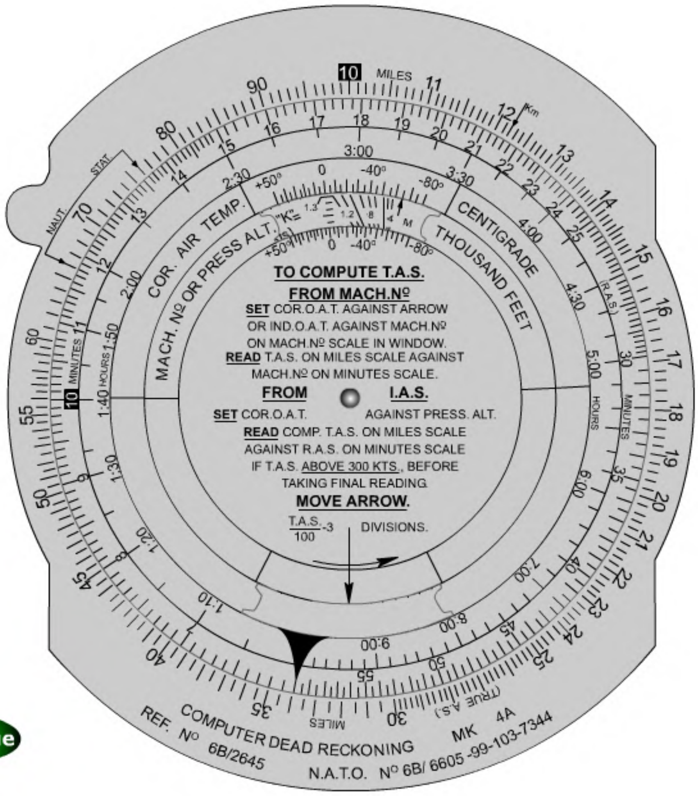

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Fig 13 – Calculating G/S (Return to text)

Problem:

If 40 nm are flown in 7 minutes, what will be the groundspeed of the aircraft?

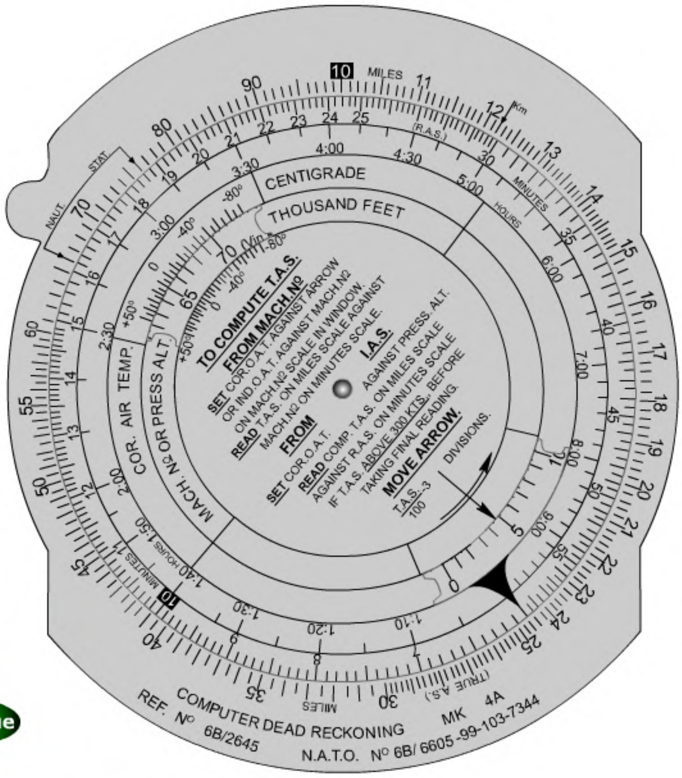

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Fig 14 – Fuel Consumption (Return to text)

Problem:

Assuming a planned fuel consumption rate of 22 kg/min, how much fuel will be used in 18 minutes?

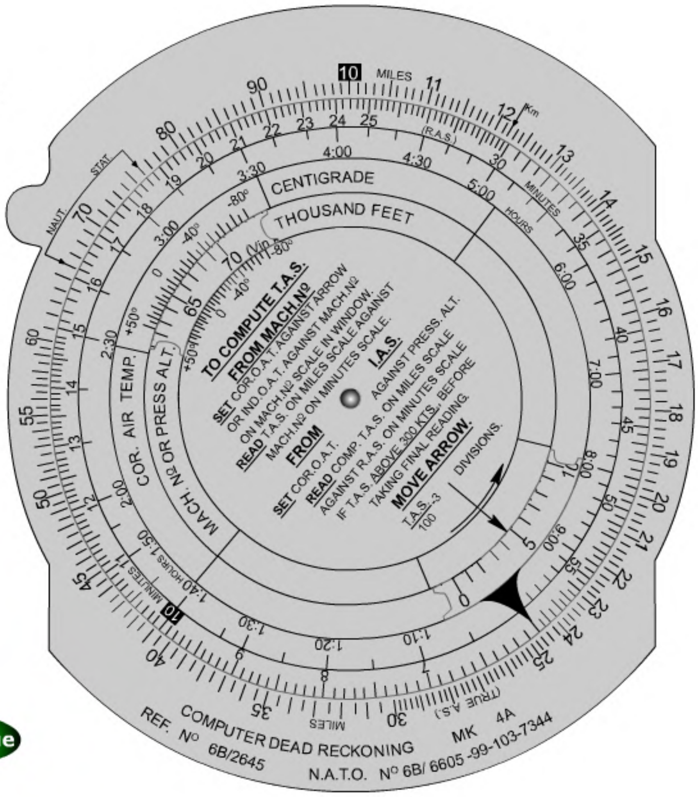

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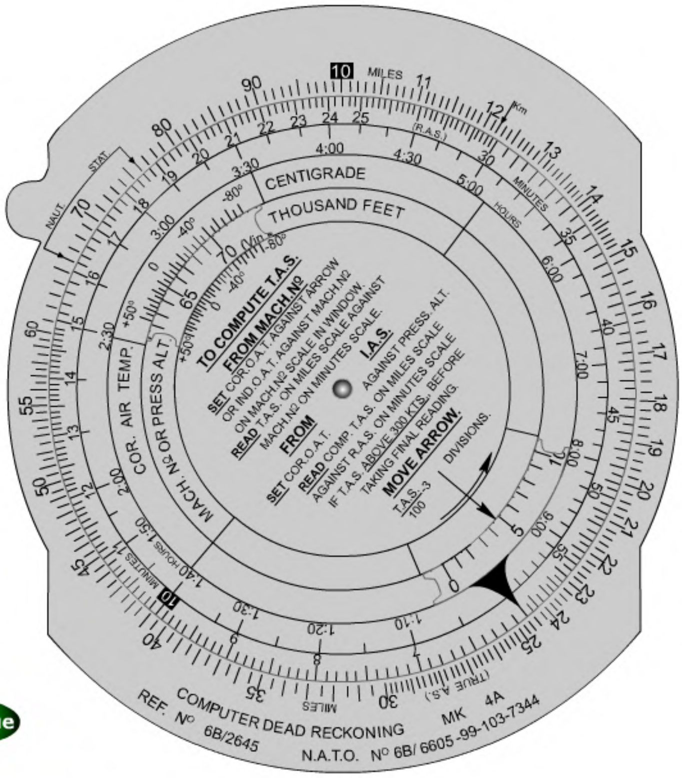
Fig 15 – Unit Conversion (Return to text)

Problem:

To convert between kilometres, nautical miles and statute miles.



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CHAPTER 9 - SUNRISE, SUNSET AND TWILIGHT

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Table of Figures

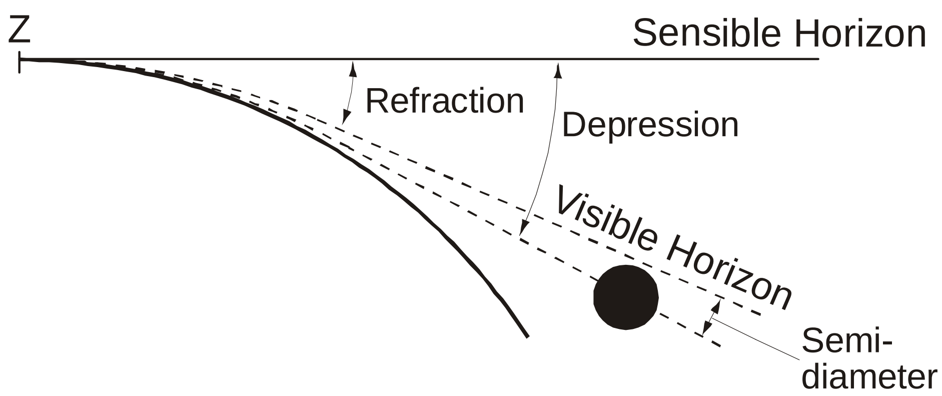
Introduction

1. The intensity of sunlight received at any point on Earth depends on the Sun's altitude[1], the maximum daily intensity being received at local noon when the Sun is at its zenith. Direct sunlight begins at sunrise and ceases at sunset when the Sun's upper rim is on the horizon. Due to the reflective properties of the atmosphere, a period of diffused light, known as twilight, precedes sunrise and follows sunset. This chapter should be read in conjunction with the UK Air Almanac which contains data regarding Sunrise and Sunset times, Moonrise and Moonset times and the duration of Twilight. The UK Air Almanac is available on the Aeronautical Information Documents Unit (AIDU) website (www.aidu.mod.uk/Milflip) and also as a free PDF download from HM Nautical Almanac Office at http://astro.ukho.gov.uk/ (www). The Almanac contains tables and graphs, along with instructions for use, to allow the user to determine the required data.

Theoretical Risings and Settings of the Sun

2. Theoretical rising and setting occurs when the Sun's centre is on the observer's celestial horizon.[2] Due to atmospheric refraction, an observer sees objects below his celestial horizon (Fig 1).

9-9 Fig 1 Sensible and Visible Horizons



SUNRISE AND SUNSET

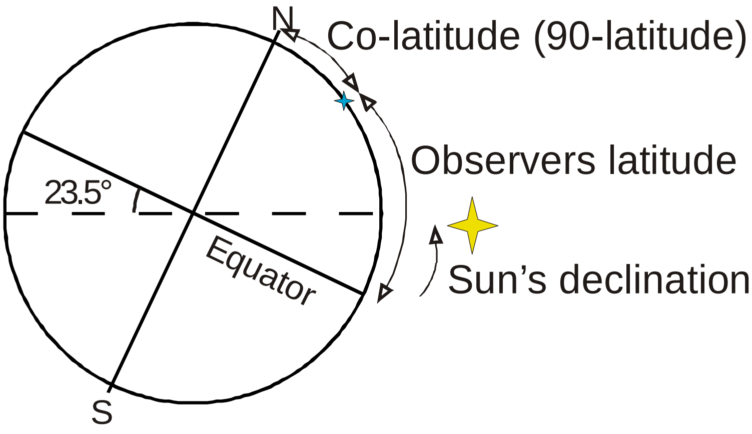
Depression

3. Sunrise and sunset are respectively defined as the point when the upper rim of the Sun just appears above (sunrise) or disappears below (sunset) the observer's visible horizon. At these times, the Sun's centre is 50' of arc below the celestial horizon. Atmospheric refraction accounts for 34' and the Sun's semi-diameter for the other 16'. The predicted times of sunrise and sunset tabulated in the Air Almanac[3] are calculated using this depression of 50' which approximates to 0.8°. The tabulated times of sunrise and sunset given in the Air Almanac are in local mean time (LMT).

Variation in Times of Sunrise and Sunset with Latitude

4. When the Sun's declination[4] (north or south of the celestial equator) is of the SAME name as the observer's latitude (north or south of the earth's equator), sunrise occurs earlier and sunset later as the observer's latitude increases. In high latitudes, when declination is greater than co-latitude (Fig 2), the Sun is continuously above the horizon. Conversely, when the Sun's declination and the observer's latitude are CONTRARY named, sunrise occurs later and sunset earlier as the observer's latitude increases.

9-9 Fig 2 Co-latitude

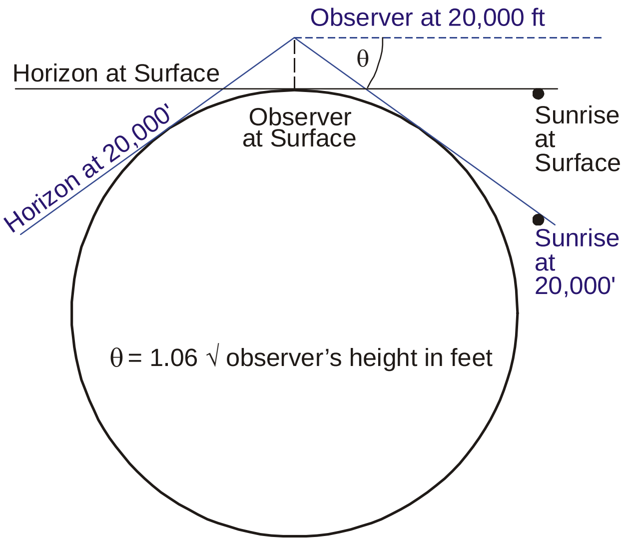


Variation in Times of Sunrise and Sunset with Height

5. The plane of the observer's visible horizon changes with change in height; sunrise becomes earlier and sunset later with an increase in height (Fig 3). θ is given by the formula:

$$\theta = 1.06\sqrt{\text{observer's height in feet}}$$

9-9 Fig 3 Effect of Height on Sunrise and Sunset



Tabulation of Sunrise and Sunset

6. Three ways of presenting the time of sunrise and sunset are given in the Air Almanac:

a. Sunrise and Sunset Tables.

b. Semi-duration of Sunlight Graphs.

c. Rising, Setting and Depression Graphs.

Full descriptions of the Table and the Graphs are given in the Air Almanac; brief descriptions are included in paragraphs 7 to 9.

7. **Sunrise and Sunset Tables**. These tables give the times of sunrise and sunset for an observer at the surface on the Greenwich Meridian between latitudes 60° S and 72° N. The Coordinated Universal

Time (UTC) of sunrise and sunset are tabulated at three-day intervals. UTC is referred to as UT in the Air Almanac. The tabulated UT of the occurrence may be taken as the local time of the occurrence at meridians other than Greenwich. The normal entering arguments are tabular date and observer's latitude. The following symbols indicate that the Sun is continuously above or below the horizon:

□ Sun continuously above horizon

■ Sun continuously below horizon.

8. **Semi-duration of Sunlight Graphs**. The times of sunrise and sunset at sea level for latitudes between 65° N and 90° N may be determined using the Semi-duration Graphs. The LMT of the Sun's transit and the semi-duration of sunlight are obtained from the graphs. The times of sunrise and sunset are found from the relationships:

LMT of sunrise = LMT of Transit – semi-duration

LMT of sunset = LMT of Transit + semi-duration.

9. **Rising, Setting and Depression Graphs**. Rising, Setting and Depression Graphs are provided for each 2° of latitude from 72° to 50° and every 5° from 50° to 0°. An associated table gives the following information:

a. Daily LMT of Sun's meridian passage.

b. Daily declination of Sun at 1200 UT.

c. Sun's depression at rising or setting for heights between 0 feet and 60,000 feet.

The semi-duration of sunlight, expressed as an hour angle, is obtained by entering the graph for the appropriate latitude with Sun's declination and the depression value corresponding to aircraft height. The LMT of sunrise and sunset are calculated by applying the semi-duration to the LMT of meridian passage. In high latitudes, a small latitude change may correspond to a large change in hour angle, and a subsidiary graph is provided for interpolation. Without interpolation, the maximum error is 12 min up to 42°, increasing to 15 min by 52°.

TWILIGHT

Types of Twilight

10. The period of diffused light before sunrise and after sunset is known as twilight. The amount of illumination varies with the Sun's depression and also with atmospheric conditions. Three twilights, each occurring at a particular depression value, are recognized:

a. **Civil Twilight**. Civil twilight occurs when the Sun's centre is 6° below the sensible horizon. Light conditions are such that everyday tasks are just possible without artificial light.

b. **Nautical Twilight**. At nautical twilight, the Sun's centre is 12° below the sensible horizon. General outlines are still discernible, and all the brighter stars are visible.

c. **Astronomical Twilight**. At astronomical twilight, the Sun's centre is 18° below the sensible horizon. All the stars are visible. Astronomical twilight is regarded as synonymous with complete darkness.

Dimensions of the Twilight Zone

11. The difference between the depression angle of the Sun at sunrise and sunset (0.8°) and that for the beginning or end of civil twilight is 5.2°, which is the dimension of the twilight zone around the earth. This, in turn, can be converted into a distance of 312 nm because 1' of arc on the surface of the Earth is equal to 1 nm.

Factors Affecting Duration and Time of Twilight

12. The duration and time of twilight for a stationary observer depend upon the following:

a. Observer's Latitude.

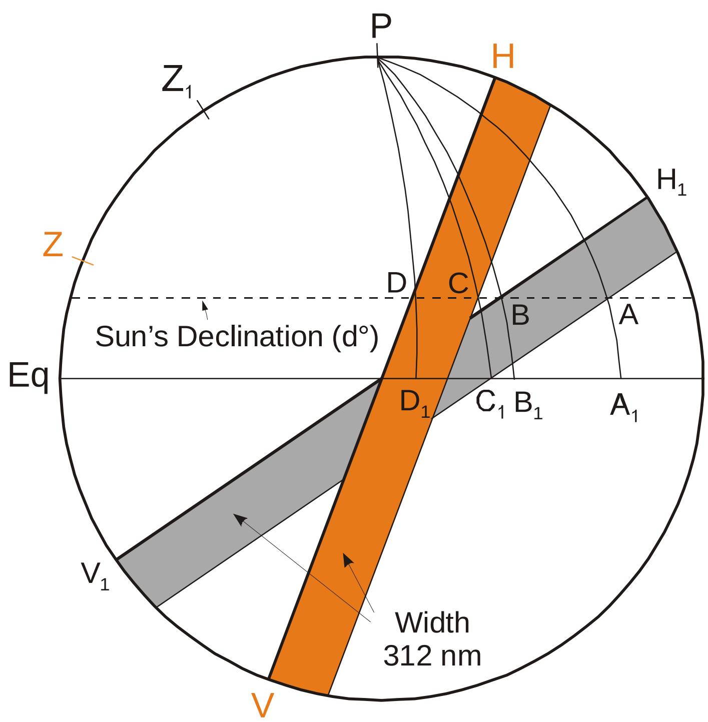
b. Sun's Declination.

c. Height of Observer above Sea Level.

Variation of Twilight with Latitude

13. Fig 4 shows two observers, Z and Z_1, their respective horizons, VH and V_1H_1, and associated twilight belts. The Sun, declination d°, crosses observer Z_1's twilight zone from A to B, the duration of twilight being A_1B_1, while for observer Z, the Sun crosses from C to D, giving duration C_1D_1. Duration A_1B_1 is greater than C_1D_1, and therefore the duration of twilight increases with increased latitude. In high latitudes, ie when same-name declination is greater than co-latitude, the Sun is continuously above the horizon. Similarly, the Sun may remain less than 6° below the horizon giving twilight conditions throughout the night. This condition is indicated by the symbol //// in the Air Almanac.

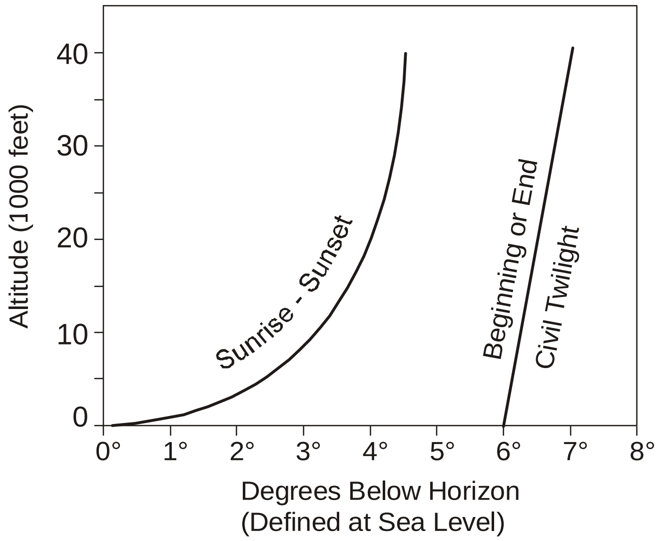
9-9 Fig 4 Variation in Duration of Twilight with Latitude



Variation of Twilight with Height

14. The Sun rises earlier and sets later with an increase in height. Morning twilight therefore occurs earlier and evening twilight later as height increases. The amount of pollution in the atmosphere decreases with height resulting in a decrease in the amount of light reflected and scattered by particles in the air. The degree of illumination associated with a depression of 6° at sea level occurs at a depression of less than 6° at height. Fig 5 shows the decrease in the duration of twilight with height.

9-9 Fig 5 Decrease in Duration of Twilight with Height



Tabulation of Duration of Twilight

15. The duration of twilight is presented in the Air Almanac, together with the times of sunrise and sunset. One table and two graphical solutions are provided. Full explanations are given in the Air Almanac, but brief descriptions are included below.

16. **Civil Twilight Tables**. The times of morning civil twilight and evening civil twilight are tabulated in the Air Almanac at three-day intervals for latitudes between 60° S and 72° N. The times given are the UT of the occurrences at sea level on the Greenwich Meridian, but the UT of the occurrences may be regarded as the LMT of the occurrences at other meridians.

17. **Duration of Twilight Graph**. The duration of Twilight graph gives the time interval between morning civil twilight and sunrise (or sunset to evening civil twilight). In the region "No Twilight nor Sunlight" the Sun is continuously more than 6° below the horizon. Adjacent to this "No Twilight nor Sunlight" region, is a region where the Sun's depression is less than 6° for part of the day, although the semi-duration of sunlight graphs show the Sun to be continuously below the horizon. In this region, the duration of twilight is the sum of the intervals between morning civil twilight and meridian passage, and meridian passage and evening civil twilight. The total duration of twilight is, therefore, double that given by the graph.

18. **Rising, Setting and Depression Graphs**. The numerical values of the depressions corresponding to specific brightness at various height are difficult to quantify. However, a particular brightness at a particular height is always associated with a specific depression value.

SUNLIGHT AND TWILIGHT IN HIGH LATITUDES

General

19. In high latitudes, the Sun may be above or below the horizon all day. Twilight conditions, where they exist, last longer than at low latitudes. In extreme cases, morning and evening twilights are continuous, the Sun remaining below the visible horizon all day.

20. The Sun's apparent path over the Earth is from East to West. An aircraft travelling westwards travels "with the Sun". If the westerly component of ground speed equals 15° of longitude per hour, the light conditions experienced remain constant. An aircraft travelling at less than 15° of westerly longitude per hour experiences a slower change of light conditions than a stationary observer on the Earth. On easterly tracks the Sun's westward velocity and the aircraft's easterly velocity combine, accelerating the normal daily change of light conditions. In the space of a few hours an aircraft might pass from daylight through evening twilight, night and morning twilight back into daylight.

21. In high latitudes, the times of sunrise, sunset, and twilight for various points along the route may be established from tables and graphs in the Air Almanac.

---

[1] **Altitude** - The angular distance between the direction to an object and the horizon. Altitude ranges from 0 degrees for an object on the horizon to 90 degrees for an object directly overhead.

[2] **Celestial Horizon** - The celestial horizon is a great circle on the celestial sphere whose plane lies at 90° to the zenith/nadir axis of an observer and passes through the centre of both the Earth and the celestial sphere.

[3] **Air Almanac** - The UK Air Almanac is available as a free PDF download from HM Nautical Almanac Office at http://astro.ukho.gov.uk/ (www).

[4] **Declination** - The angular distance of a celestial body north or south of the celestial equator. Declination is analogous to latitude in the terrestrial coordinate system.

CHAPTER 10 - THE MOON

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Table of Figures

GENERAL

Introduction

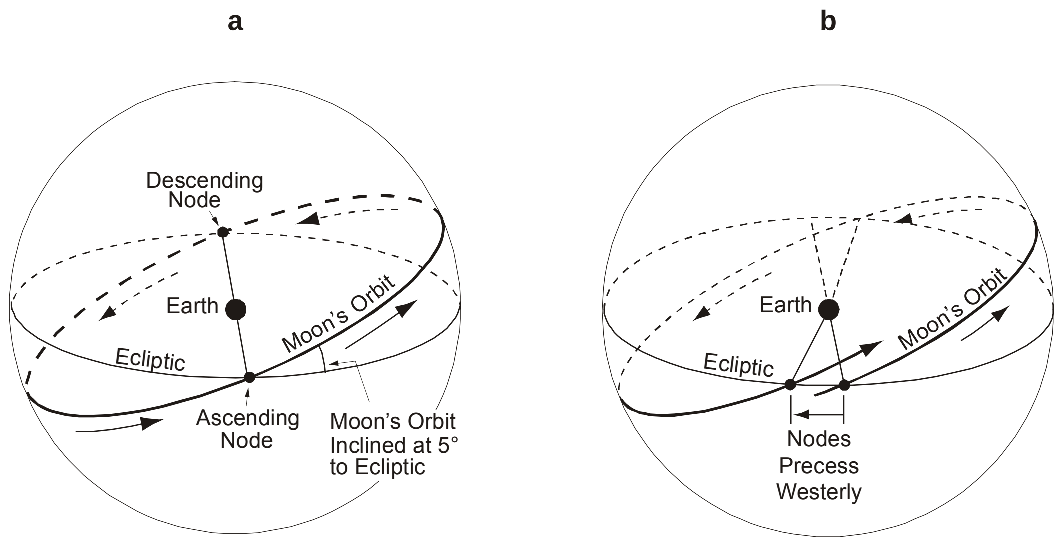
1. The Moon is the Earth's only natural satellite. Because of its short period of revolution about the Earth, the Moon's position on the celestial sphere[1] is constantly changing. Like the planets, the Moon is not self-luminous, but shines by reflecting sunlight. The intensity of moonlight varies with the Moon's phase.

THE MOON'S ORBIT

General

2. The Moon revolves around the Earth in an elliptical orbit in accordance with Kepler's first law[2], modified by perturbations caused by the sun. The orbit is inclined at 5° to the ecliptic, the points of intersection between the orbit and the ecliptic being known as the Ascending and Descending Nodes (Fig 1). The Moon's Nodes precess westwards along the ecliptic, completing one revolution in 18.6 years.

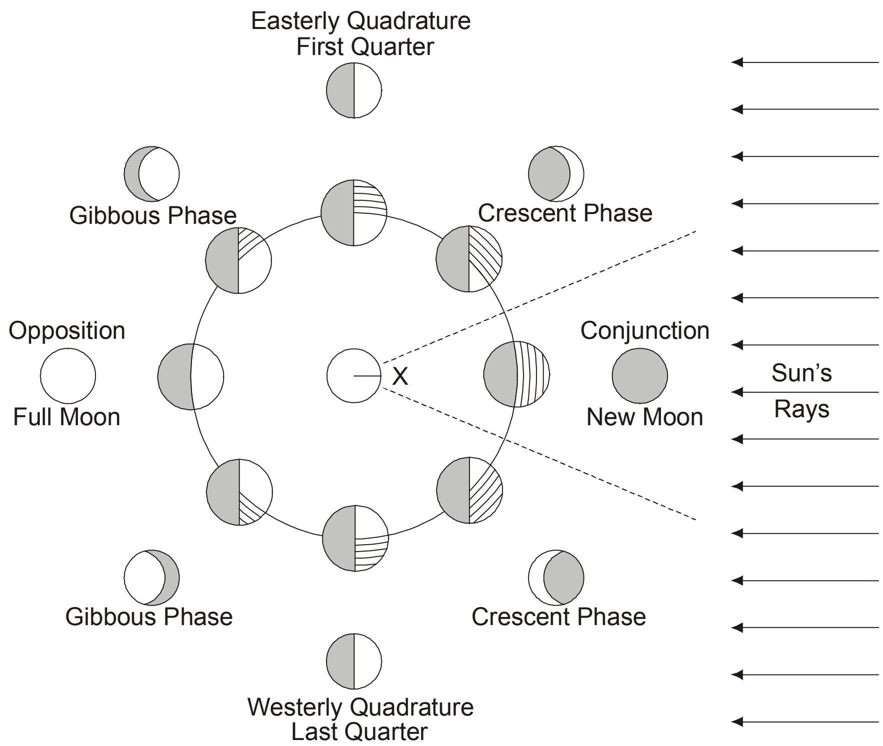
9-10 Fig 1 Motion of the Moon Relative to Ecliptic



The Moon's Phases

3. Seen from Earth, the phase[3] or shape of the Moon depends on the Moon's position relative to the Sun and on the angle at which the Moon's illuminated hemisphere is presented to the Earth. The eight phases of the Moon, in Fig 2, are drawn as they appear to an observer on Earth, ie looking outwards from the centre of the diagram.

9-10 Fig 2 Phases of the Moon



4. The interval between successive New Moons is approximately 29.5 days. The Moon's age is measured in days from the New Moon. At New Moon the Moon's age is 0 days and at First Quarter about 7 days. Full Moon occurs about 15 days and Last Quarter about 22 days. The Moon's age is given in the Air Almanac[4].

5. At New Moon, the Moon and the Sun are over the observer's meridian at the same time, ie local noon. When the Moon is above the horizon in the periods immediately preceding and following New Moon, the illuminated portion of the Moon presented to the observer is too small to be seen against the sunlight. The Moon crosses the observer's meridian at 1800 Local Mean Time (LMT) at the First Quarter, 2400 LMT at Full Moon, and 0600 LMT at Last Quarter.

MOONRISE AND MOONSET

Visible Rising and Setting

6. The Moon's visible risings and settings occur when the Moon's upper rim is just on the visible horizon. The Moon's average altitude at visible rising and setting is +7' of arc:

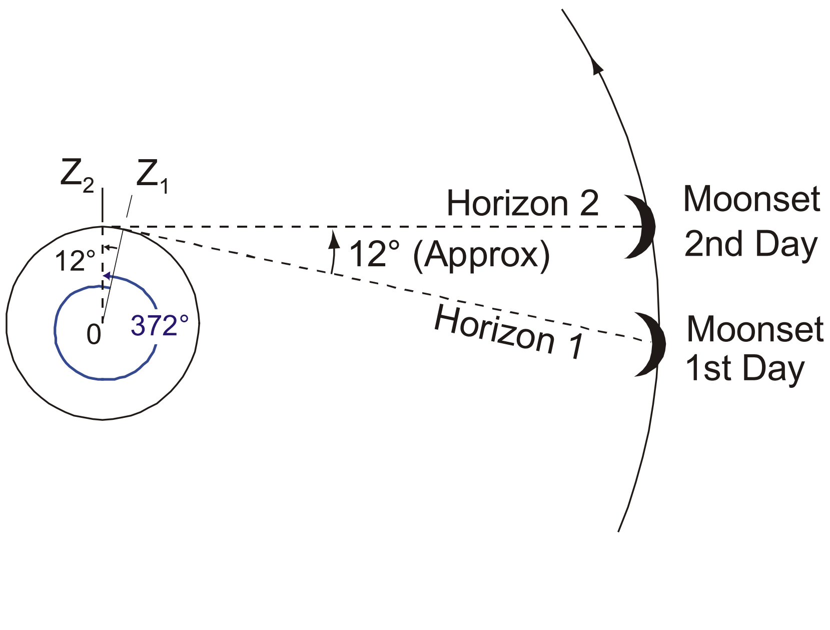
H_O upper rim	=	00º 00'
Atmospheric Refraction	=	– 34'
Semi Diameter	=	– 16'
Horizontal Parallax	=	+ 57' (average)
H_O Moon's Centre	=	+ 7'

Because of the varying distances between the Moon and the Earth the value of horizontal parallax varies between 54' and 61'. In practice, the times of visible rising and setting given in the Air Almanac are calculated using an altitude of (–50' + HP), where HP is the actual value of horizontal parallax at the time of the occurrence.

Retrograde Motion of the Moon

7. Calculation of the times of moonrise and moonset at longitudes other than Greenwich is complicated by the Moon's movement around its orbit. The Moon moves around its orbit in the same direction as the Earth's rotation, completing one orbit in approximately 29.5 days. The average daily movement along the orbit is approximately 12°, or 48 minutes of time. In Fig 3, Z_1 and Z_2 are the positions of successive moonsets, the Moon's declination being assumed constant. During the time it takes the Earth to rotate through 360°, the Moon moves 12° along its orbit. Moonset on the second day occurs at Z_2 and not Z_1. The observer moves 372° between moonsets, i.e. the elapsed time between moonsets is 24 hours 48 minutes.

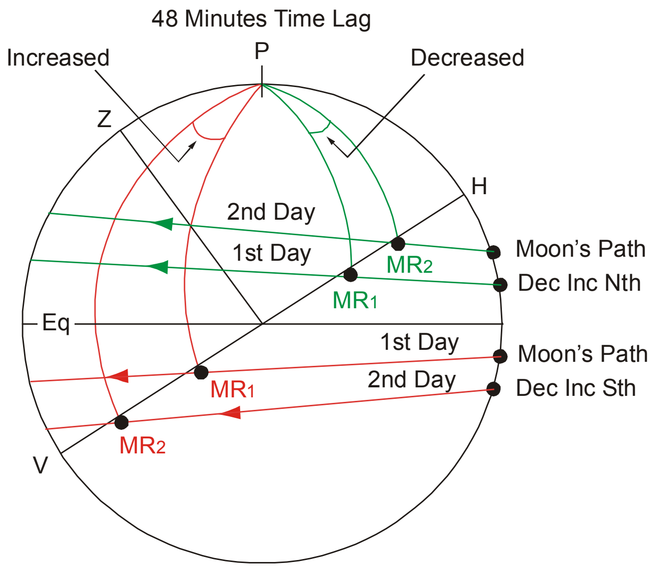
9-10 Fig 3 Retrograde Motion of the Moon



Effect of Declination Changes on Times of Moonrise and Moonset

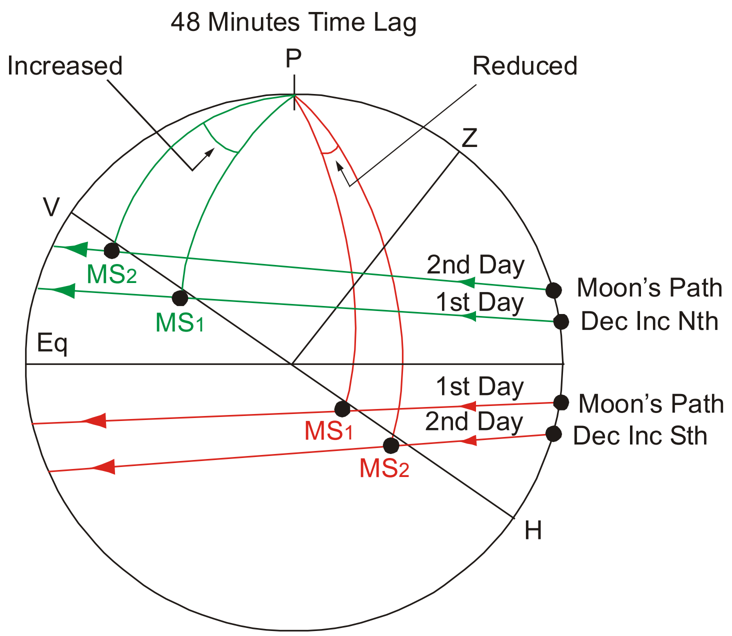
8. The daily change in declination[5] can be sufficiently great to have a considerable effect on the times of moonrise and moonset. When the Moon's declination is increasing, the daily time lag of 48 minutes in the time of moonrise reduces for SAME name declinations and increases for CONTRARY name declinations. Conversely, when the Moon's declination is decreasing, the daily time lag is increased for SAME name declinations and decreases for CONTRARY name declinations (Fig 4).

9-10 Fig 4 Effect of Declination Changes on Time of Moonrise



9. The effect of the declination changes on the time of moonset is reversed. When declination is increasing, the time lag, increases for SAME name declinations, and decreases for CONTRARY name declinations (Fig 5).

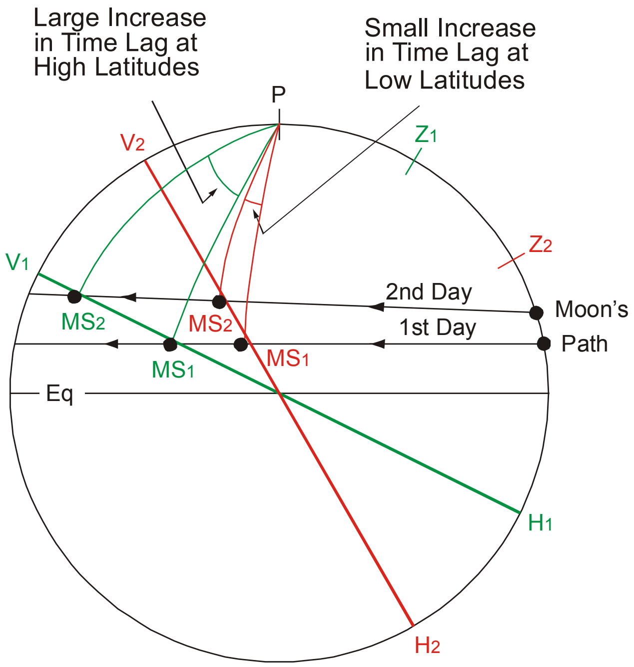
9-10 Fig 5 Effect of Declination Changes on Time of Moonset



Effect of Latitude on Times of Moonrise and Moonset

10. For any given daily change of declination, the effect on the times of moonrise and moonset increases with latitude. In Fig 6, the Moon's declination has the SAME name and is increasing. The time of moonset on both days is shown. The increase in time lag experienced by observer Z_1 is larger than the increase experienced by observer Z_2.

9-10 Fig 6 Effect of Latitude



Effect of Longitude on Times of Moonrise and Moonset

11. Due to the above effects, the LMT of moonrise and moonset at the Greenwich Meridian cannot be considered the LMT of the occurrences at other meridians. The difference between the times of the occurrences at Greenwich and the times of the occurrences at the 180° E/W meridian are calculated and tabulated in the Air Almanac. Since the rate of change of declination is almost constant, the difference between the time of an occurrence at Greenwich and the time at any other meridian may be found by simple proportion. A simple proportion table is provided to facilitate interpolation for intermediate longitudes. The corrected difference is applied to the LMT of the occurrence at Greenwich to give the LMT of the occurrence at the desired longitude.

Effect of Height on Times of Moonrise and Moonset

12. The effect of height on the times of moonrise and moonset is complicated by the Moon's rapid movement and is therefore ignored.

Variations in the Daily Time Lag and their Effect on Moonrise and Moonset

13. The 48 minute difference between the time of successive moonrise and moonset is modified by the effects of latitude and declination, but the overall interval between successive phenomena is usually greater than 24 hours. When the observer's latitude exceeds the complement of the obliquity

of the Moon's orbit, the daily declination change may not only cancel out the 48-minute time lag, but reduce the time between successive risings or settings to less than 24 hours.

14. When the interval between successive phenomena is less than 24 hours, the Moon may rise and set twice in one day. Both times are given in the Air Almanac. Each month, around the last quarter, there is one day without a moonrise, and another, around the first quarter, without a moonset. On these occasions, the time of the following moonrise or moonset at Greenwich will be later than 2400, e.g. 2420. This time, e.g. 2420, is given to facilitate the calculation of the times of the phenomena at other longitudes.

Tabulation of Times of Moonrise and Moonset

15. **Daily Tables**. The LMT of moonrise and moonset at latitudes between 60° S and 72° N on the Greenwich Meridian are tabulated in the Air Almanac. The LMT of the occurrences at longitudes other than Greenwich are established using the tabulated differences and the interpolation table discussed in para 11. When calculating the LMT of moonrise and moonset for a particular day, the time calculated may be in the previous or the following day; the time of the occurrence at Greenwich is for the required day, but the addition or subtraction of the difference correction may move the LMT of the occurrence into the previous or the following day. The LMT of the occurrence is then found by adding or subtracting 24 hours plus twice the tabulated difference. Twice the difference is applied because the difference correction to 360° of longitude is required, and the difference tabulated is for 180° of longitude.

16. **Semi-Duration of Moonlight Graphs**. The Semi-Duration of Moonlight Graphs give the LMT of the Moon's meridian passage and the semi-duration of moonlight for latitudes above 65° N. The times of meridian passage and the semi-durations change rapidly, and care must be taken to read the graphs accurately.

17. **Use of Moonlight Graphs**. A rough idea of the times of moonrise and moonset may be obtained from a superficial examination of the graphs. The vertical from the appropriate date cuts the top scale at the LMT of meridian passage. The intersection of the vertical with the appropriate latitude line gives the semi-duration of moonlight. The semi-duration is added to and subtracted from the LMT of meridian passage to give the times of moonset and moonrise respectively. The times obtained are the LMT of the occurrences on the Greenwich Meridian. The times at meridians other than Greenwich may be obtained by either of the following methods:

a. The LMT of moonrise and moonset on the Greenwich Meridian is calculated for the required date and either the following date or the preceding date. The difference in the times represents the effect of a 360° change of longitude. The time of moonrise or moonset at the desired meridian is then established by proportioning the 360° difference.

b. The dates on the graph correspond to 00 hrs LMT at the Greenwich Meridian. The times of meridian passage, moonrise and moonset are estimated directly from the graphs. The times extracted are converted to the UT at the desired longitude. The graph is re-entered at the point on the daily scale corresponding to the UT of meridian passage at the desired longitude, and a new value of LMT meridian passage obtained. Similarly, the UT of moonrise and moonset are used to establish further semi-duration values. The LMT of moonrise and moonset are obtained by applying the new semi-duration values to the new time of meridian passage.

---

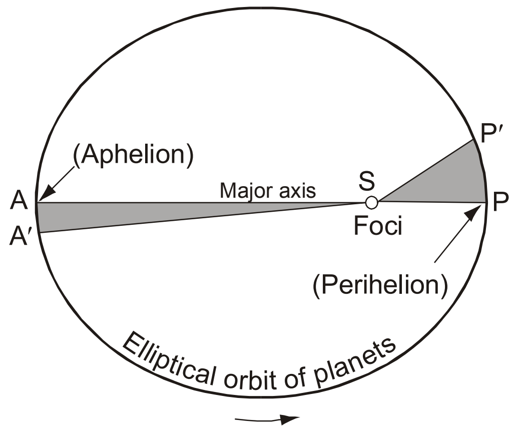
[1] **Celestial Sphere** - The celestial sphere is an imaginary sphere of infinite radius, concentric with the Earth, on which all celestial bodies are imagined to be projected.

[2] **Kepler's Laws** - Kepler defined the following laws of planetary motion:

a. The orbit of each planet is an ellipse, with the Sun at one of the foci.

b. The line joining the planet to the Sun sweeps across equal areas in equal times.

c. The square of the sidereal period of a planet is proportional to the cube of its mean distance from the Sun.



[3] **Moon – Phases**

Crescent Phase - The phase of the moon at which only a small, crescent-shaped portion of the near side of the Moon is illuminated by sunlight. Crescent phase occurs just before and after new moon.
Full Phase - The phase of the moon at which the bright side of the Moon is the face turned toward the Earth.
New Phase - The phase of the moon in which none or almost none of the near side of the Moon is illuminated by sunlight, so the near side appears dark.
Quarter phase - The phase of the moon in which half of the near side of the Moon is illuminated by the Sun.
Waning Crescent - The Moon's crescent phase that occurs just before new moon.
Waxing Crescent - The Moon's crescent phase that occurs just after new moon.

[4] **Air Almanac** - The UK Air Almanac is available as a free PDF download from HM Nautical Almanac Office at http://astro.ukho.gov.uk/ (www).

[5] **Declination** - The angular distance of a celestial body north or south of the celestial equator. Declination is analogous to latitude in the terrestrial coordinate system.

CHAPTER 11 - TIME

Contents **Page**

Table of Figures

Introduction

1. From the earliest days, time has been measured by observing the recurrence of astronomical phenomena. The Earth's rotation on its axis produces the apparent rotation of the celestial sphere[1], allowing time to be measured from the relative positions of an astronomical reference point and a specific celestial meridian.

2. Nowadays, the fundamental properties of the atom are utilized to provide an independent basis for time measurement. The atomic time-scale provides a precise measurement of time intervals, the summation of these time intervals providing an accurate measure of the passage of time. Atomic time is not related to "time of day", but the starting point of any period of atomic time may be specified in terms of an astronomical instant.

THE DAY AND THE YEAR

General

3. The Earth's rotation on its axis, and its revolution around the Sun, result in the natural time intervals of the day and the year.

The Day

4. The day is the duration of one rotation of the Earth on its axis, and is the interval between two successive transits of a celestial reference point over a particular meridian.

Apparent Solar Day

5. The visible Sun is known as the apparent or true Sun, and the apparent solar day is the interval between two successive transits of the apparent Sun over a particular meridian. The Earth's variable speed along the ecliptic (Kepler's 2nd Law) causes variations in the length of the apparent solar day.

Mean Solar Day

6. A day of constantly changing length is inconvenient, and therefore the mean solar day of constant length is used, the length being based on the average of all apparent solar days over a period of years. Mean solar time is measured relative to the mean or astronomical mean Sun, a fictitious body assumed to travel around the equinoctial at a constant rate. The mean solar day is divided into 24 hours, each hour of 60 minutes, and each minute of 60 seconds of mean solar time or mean time.

7. The astronomical mean Sun must have a constant angular velocity in the plane of the equinoctial; a constant angular velocity in the plane of the ecliptic is unsatisfactory because the rate of change of hour angle fluctuates due to meridian convergence.

Equation of Time

8. Mean time increases at a constant rate while apparent time increases at a variable rate. The difference between mean and apparent time is known as the Equation of Time (E). E is not an equation in the normal sense, but merely a time difference. E is positive when apparent noon precedes mean noon and negative when apparent noon follows mean noon. By convention, E is the amount which is added algebraically to mean time to obtain apparent time.

THE YEAR

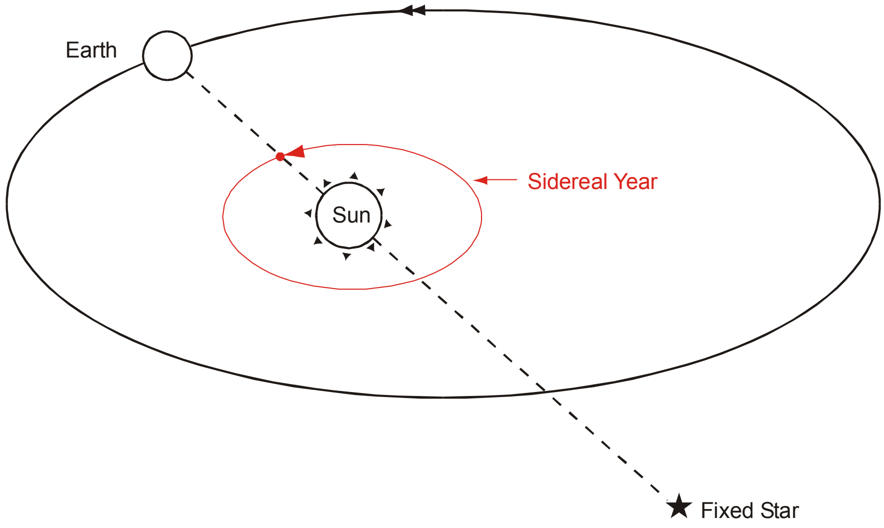
Introduction

9. One year is the period of one revolution of the Earth about the Sun relative to an astronomical reference. The type of year takes its name from the reference used.

Sidereal Year

10. The sidereal year is the period between two successive conjunctions of the Earth, Sun, and a fixed point in space (Fig 1).

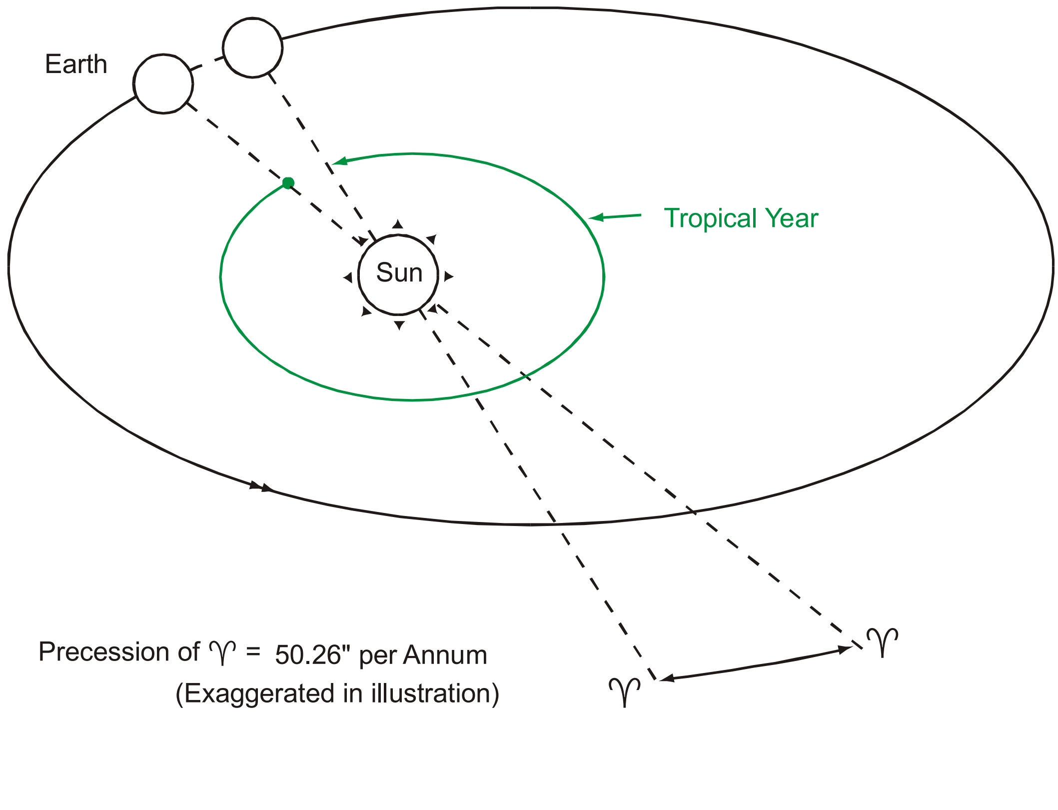
9-11 Fig 1 Sidereal Year



Tropical Year

11. The tropical year (Fig 2) is the period between two successive vernal equinoxes[2], i.e. the time taken for one orbit around the Sun relative to the First Point of Aries (♈)[3]. The tropical year contains one complete cycle of seasons. Its length is 365 days 5 hours 48 minutes 45.98 seconds, which is shorter than the sidereal year because of the westward precession of the equinoxes.

9-11 Fig 2 Tropical Year



Civil Year

12. The civil year is based on the tropical year, but the calendar is adjusted to give each year an exact number of days.

Gregorian Calendar

13. The Gregorian calendar assumes the length of a normal year to be 365 days, with every fourth year being a leap year containing 366 days. After four years, the civil year and the tropical year differ by 45 minutes, ie the calendar and the seasons are out of step by 45 minutes.

4 Civil Years	=	4 × 365 days + 1 day
	=	1,461 days
4 Tropical Years	=	1,460 days 23 hours 15 minutes.

After 400 years, the difference has increased to 3 days 3 hours. To correct for this, nearly every year whose number is a multiple of 100 (i.e. at the turn of each century) is treated as an ordinary year of 365 days, even though it can be divided by 4. Only when the century number (i.e. the first two figures of the year) is divisible by four, is it a leap year. This adjustment loses three days every 400 years, and is known as the Gregorian Correction. At the end of 4,000 years the total error will be 1 day 4 hours 55 minutes.

Time and Hour Angle

14. The Earth rotates once in 24 hours relative to the mean Sun. 360° of hour angle is equivalent to 24 hours of mean solar time or mean time. Hour angle is therefore interchangeable with mean time:

$$
\begin{aligned}
360^\circ &\equiv 24 \text{ hours} \\
15^\circ &\equiv 1 \text{ hour} \\
15' &\equiv 1 \text{ minute} \\
15'' &\equiv 1 \text{ second.}
\end{aligned}
$$

Local Mean Time

15. Local Mean Time (LMT) is defined as the arc of the equinoctial intercepted between the observer's anti-meridian and the meridian of the mean Sun measured westwards, i.e. the elapsed time since the mean Sun's transit of the observer's celestial anti-meridian:

$$\text{LMT} = \text{local hour angle mean Sun (LHAMS)} \pm 12 \text{ hours.}$$

The anti-meridian is used so that the local date changes during the hours of darkness. The mean Sun crosses an observer's meridian at 1200 LMT, ie local noon.

16. Since LMT depends upon LHAMS, LMT varies with longitude; LMT at one longitude is converted to LMT at another longitude by applying the ch long converted to time. Ch long East, in hours and minutes, is added to LMT at the original longitude to obtain LMT at the desired longitude:

$$\text{LMT}_2 = \text{LMT}_1 \begin{array}{l} +\text{E ch long} \\ -\text{W ch long} \end{array}$$

a. **Example 1**. LMT and local date (LD) are 03.10.00 on 2 August at Longitude 12° W. Find LMT and LD at longitude 33° E.

LMT at 12° W	=	03.10.00 on 2 Aug
Ch long 45° E	≡	+03 (see para 20)
LMT at 33° E	=	06.10.00 on 2 Aug.

Note. The date must be included in all time problems. Where the sum of the original time and ch long exceeds 24 hours, the date is increased by one day. Conversely, where the sum is less, i.e. a negative value, the date is decreased by one day.

b. **Example 2**. LMT and LD are 09.40.00 at longitude 46° E on 2 August. Find LMT and LD in longitude 110° W.

LMT at 46° E	=	09.40.00 on 2 Aug
Ch long 156° W	≡	– 10.24.00
∴ LMT at 110° W	=	– 00.44.00 on 2 Aug
	=	23.16.00 on 1 Aug.

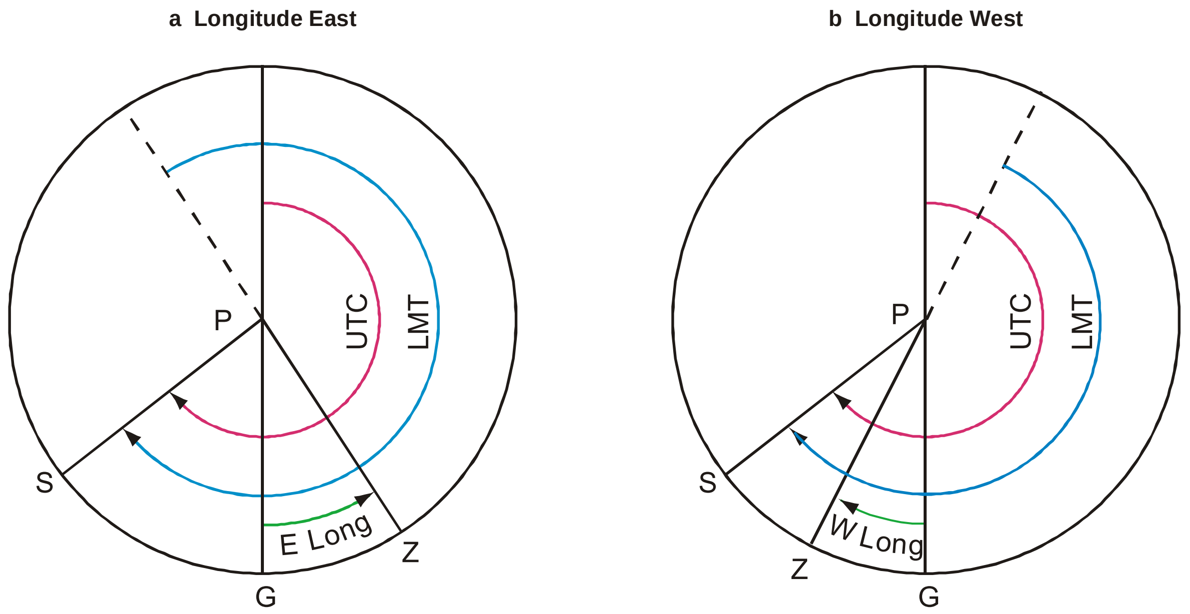
Coordinated Universal Time (UTC)

17. UTC is used as the world standard of reference time. For all practical purposes it can be regarded as LMT at the Greenwich Meridian. UTC can therefore be converted to LMT at any other meridian by applying longitude, converted to time:

$$\text{LMT} = \text{UTC} \begin{array}{l} +\text{ long E} \\ -\text{ long W} \end{array}$$

The relationship between UTC and LMT is illustrated in Figs 3a and 3b. G represents the Greenwich Meridian, Z the observer's meridian and S is the Sun's meridian.

9-11 Fig 3 Relationship Between UTC and LMT



a. **Example 3**. Find LMT at longitude 26° E when UTC is 10.30.00 on 2 August.

UTC	=	10.30.00 on 2 Aug
26° E	≡	+ 01.44.00
LMT	=	12.14.00 on 2 Aug

b. **Example 4**. Find the LMT at longitude 120° E, when UTC is 19.32.00 and Greenwich Date (GD) is 2 August.

UTC	=	19.32.00 on 2 Aug
120° E	≡	+ 08.00.00
LMT	=	27.32.00 on 2 Aug
	=	03.32.00 on 3 Aug

18. UTC and LMT are both unsuitable for regulating time in particular areas; UTC is in step with the phenomena of day and night only at the Greenwich Meridian, and all longitude changes, however small, result in changes in LMT. Zone time and standard time overcome the problems, being approximately in step with night and day, and having the additional advantage that time remains uniform in particular areas.

Zone Time

19. The Earth is divided, purely by longitude, into 25 zones, all of which are 15° of longitude (or 1 hour) wide, except for the two semi-zones adjacent to the International Date Line (approximately 180° E/W - see para 25). The central meridians of the zones are removed from the Greenwich meridian by multiples of 15° and the extremities of the zones are bounded by meridians 7.5° removed from the central meridian. The zones are each allocated an identifying letter as shown in Fig 4.

20. The zone time is the LMT of its central meridian, and therefore zone time differs from UTC by multiples of one hour. Furthermore zone time is related to sun time ± 30 minutes.

21. The number of hours difference between zone time and UTC can be calculated by dividing the longitude by 15 and approximating the result to the nearest whole number, e.g.:

A ship at 48° W shows a zone time of 1800 hours on 2 August ie 1800 hours P. What is the UTC?

Dividing 48 by 15 gives 3.2, which is 3 to the nearest whole number. Therefore UTC is 3 hours different from zone time. As the longitude is West the 3 hours must be added to zone time to find UTC. UTC is thus 2100 hours on August 2.

Standard Time

22. Each national authority throughout the world has decreed that a particular LMT shall be kept throughout its country; this time is known as standard time. In those countries with a significant east-west extent, such as the USA and Australia, further subdivision is necessary. Although the standard times, in general, approximate to zone time, the boundaries tend to follow natural features such as rivers or mountain ranges, or national or state borders, and are not tied to specific longitudinal changes.

23. Standard times mostly differ from UTC by whole numbers of hours and the Air Almanac contains three lists showing the differences between UTC and the standard times kept throughout the world. List **I** shows those places fast on UTC (mainly East of Greenwich), list **II** those places keeping UTC, and list **III** those places slow on UTC (West of Greenwich).

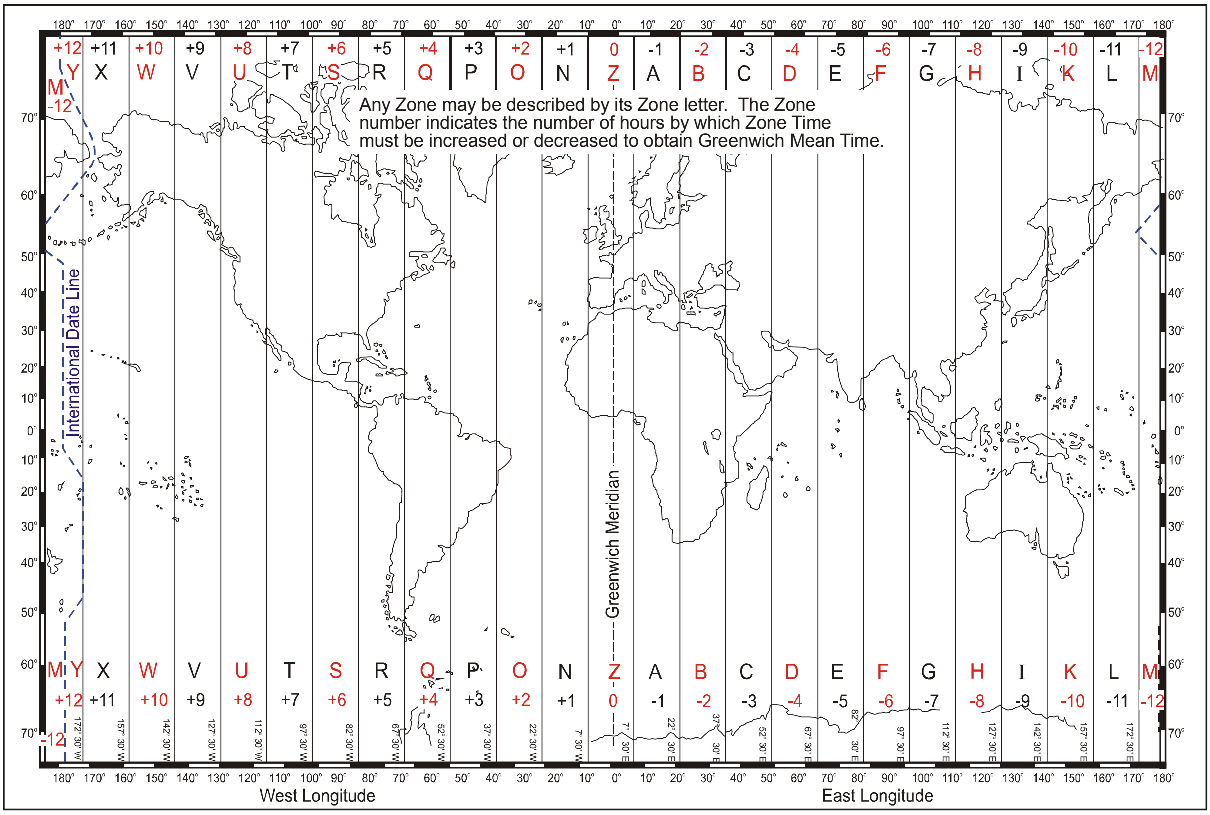
24. Many countries keep summer, or daylight saving time, which is one hour fast on standard time, for all or part of the year. Such variations are noted in the Air Almanac.

International Date Line

25. The LMT of places east of Greenwich are ahead of UTC, and places west of Greenwich behind UTC, LMT on the Greenwich anti-meridian is therefore either 12 hours ahead or 12 hours behind UTC. There is a 24-hour time difference between neighbouring places separated by the Greenwich anti-meridian, ie local date changes on crossing the Greenwich anti-meridian.

26. The Greenwich anti-meridian is called the International Date Line. This date line deviates from the anti-meridian in places, to avoid date changes occurring in the middle of populated regions. The International Date Line is illustrated in Fig 4. On crossing the date line, one day is added on westerly tracks and subtracted on easterly tracks. Since zone time and standard time are based on Greenwich, there is also a change of one day in zone date and standard date when crossing the International Date Line.

9-11 Fig 4 Time Zones



TIME REFERENCES

Atomic Time

27. The atomic time standard is based on the fundamental properties of the caesium atom and forms the basis of the world standard of time, (UTC). Previously, the LMT at the Greenwich meridian was used as the standard and this is known as Greenwich Mean Time (GMT). Whereas UTC increases at a constant rate, GMT, which is a measure of the Earth's rotation on its axis, increases at a variable rate due to tidal friction and other periodic changes. The variations in GMT are small, varying between – 0.5 seconds and + 2.5 seconds a year, but UTC must be corrected for the variations before it equals GMT.

28. All primary time signals give UTC, and a coded correction is included to enable UTC to be converted to GMT to an accuracy of 0.1 second. By international agreement, UTC is allowed to depart from GMT by 0.7 seconds. When the correction reaches 0.7 seconds, a positive or negative leap second is applied to UTC. For all normal air navigation purposes UTC and GMT can be regarded as identical since the maximum error involved is 0.7 seconds.

Radio Time Signals

28. Numerous national and commercial broadcast stations throughout the world transmit frequent time signals whose accuracy is sufficient for all navigation purposes. Primary and secondary transmission sources are recognized and, whereas all stations transmit UTC, the primary transmissions include the coded correction that can be applied to UTC to obtain GMT accurate to 0.1 second. Some of the more important time signals are included in the Flight Information Handbook together with their transmission frequency and time.

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[1] **Celestial Sphere** - The celestial sphere is an imaginary sphere of infinite radius, concentric with the Earth, on which all celestial bodies are imagined to be projected.

[2] **Vernal Equinox** - The point in the sky where the Sun appears to cross the celestial equator moving from south to north. This happens approximately on March 21.

[3] **Aries** - **First Point of Aries (♈)** (**vernal** (**spring**) **equinox**) Over the course of a year the Sun, moving along its annual path, crosses the equator from south to north and again from north to south. These crossings occur on or near 21 March and 23 September and are known as the vernal (spring) and autumn equinoxes respectively. The vernal equinox is also known as the First Point of Aries (♈).

CHAPTER 12 – GLOSSARY OF ASTRONOMICAL TERMS

Air Almanac - The UK Air Almanac is available as a free PDF download from HM Nautical Almanac Office at http://astro.ukho.gov.uk/ (www).

Altitude - The angular distance between the direction to an object and the horizon. Altitude ranges from 0 degrees for an object on the horizon to 90 degrees for an object directly overhead.

Angular Momentum - The momentum of a body associated with its rotation or revolution. For a body in a circular orbit, angular momentum is the product of orbital distance, orbital speed, and mass. When two bodies collide or interact, angular momentum is conserved.

Aphelion - The point in the orbit of a solar system body where it is farthest from the Sun.

Apogee - The apogee is the point in the orbit of the Moon, planet or other artifical satellite farthest from the Earth.

Apparent Brightness - The observed brightness of a celestial body.

Apparent Magnitude - The observed magnitude of a celestial body.

Apparent Solar Day - The amount of time that passes between successive appearances of the Sun on the meridian. The apparent solar day varies in length throughout the year.

Apparent Solar Time - Time kept according to the actual position of the Sun in the sky. Apparent solar noon occurs when the Sun crosses an observer's meridian.

Aries - **First Point of Aries (♈)** (**vernal** (**spring**) **equinox**) Over the course of a year the Sun, moving along its annual path, crosses the equator from south to north and again from north to south. These crossings occur on or near 21 March and 23 September and are known as the vernal (spring) and autumn equinoxes respectively. The vernal equinox is also known as the First Point of Aries (♈).

Ascending Node - The point in the Moon's orbit where it crosses the ecliptic from south to north.

Autumnal Equinox - The point in the sky where the Sun appears to cross the celestial equator moving from north to south. This happens on approximately September 22.

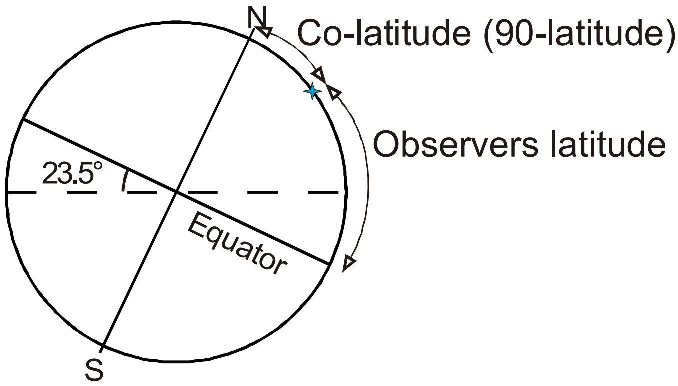
Azimuth - The angular distance between the north point on the horizon eastward around the horizon to the point on the horizon nearest to the direction to a celestial body.

Celestial Equator - The circle where the Earth's equator, if extended outward into space, would intersect the celestial sphere.

Celestial Horizon - The celestial horizon is a great circle on the celestial sphere whose plane lies at 90° to the zenith/nadir axis of an observer and passes through the centre of both the Earth and the celestial sphere.

Celestial Sphere - The celestial sphere is an imaginary sphere of infinite radius, concentric with the Earth, on which all celestial bodies are imagined to be projected.

Co-latitude – Co-latitude is 90º - latitude.



Coriolis Effect - The acceleration which a body experiences when it moves across the surface of a rotating body. The acceleration results in a westward deflection of projectiles and currents of air or water when they move toward the Earth's equator and an eastward deflection when they move away from the equator.

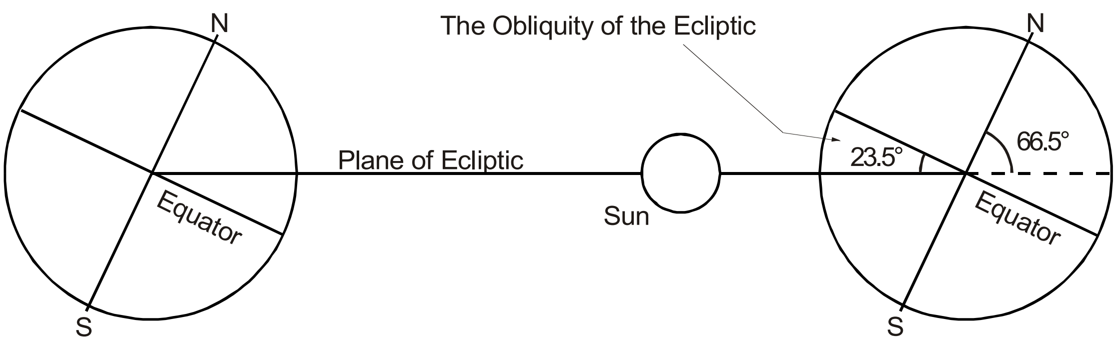
Declination - The angular distance of a celestial body north or south of the celestial equator. Declination is analogous to latitude in the terrestrial coordinate system.

Descending Node - The point in the Moon's orbit where it crosses the ecliptic from north to south.

Diurnal – Daily.

Diurnal Circle - The circular path that a celestial body traces out as it appears to move across the sky during an entire day. Diurnal circles are centered on the north and south celestial poles.

Earth Orbit - The Earth completes one orbit round the Sun in approximately 365.25 days. The orbital plane is called the **ecliptic**. The Earth's N-S axis is inclined at 66.5º to the ecliptic. The plane of the ecliptic makes an angle of 23.5º with the plane of the Earth's equator; this angle is known as the **obliquity of the ecliptic**.



Earth Rotation - The Earth rotates from west to east on its axis as it orbits the Sun. The Sun's apparent daily path over the Earth is along a parallel of latitude, the particular latitude depending on the position of the Sun along its apparent annual path. Since the Earth rotates from west to east, the apparent daily movement of the Sun and all other astronomical bodies is east to west.

Earth Seasons - The tilting of the Earth's axis causes the annual cycle of seasons. The projection of the Sun's apparent annual path on the Earth is a great circle inclined at 23.5º to the equator. About 23 December, the North Pole is inclined directly away from the Sun, which is overhead the 23.5º South parallel. Known as the winter solstice, this is winter in the northern hemisphere and summer in the southern hemisphere.

Eccentricity - A measure of the extent to which an orbit departs from circularity. Eccentricity ranges from 0.0 for a circle to 1.0 for a parabola.

Eclipse - The obscuration of the light from the Sun when the observer enters the Moon's shadow or the Moon when it enters the Earth's shadow. Also, the obscuration of a star when it passes behind its binary companion.

Eclipse Year - The interval of time (346.6 days) from one passage of the Sun through a node of the Moon's orbit to the next passage through the same node.

Ecliptic - The plane of the Earth's orbit about the Sun. As a result of the Earth's motion, the Sun appears to move among the stars, following a path that is also called the ecliptic.

Ellipse - A closed, elongated curve describing the shape of the orbit that one body follows about another.

Equator - The line around the surface of a rotating body that is midway between the rotational poles. The equator divides the body into northern and southern hemispheres.

Equatorial System - A coordinate system, using right ascension and declination as coordinates, used to describe the angular location of bodies in the sky.

Equinoctial - The equinoctial is the primary great circle of the celestial sphere, and is formed by the projection of the Earth's equator onto the celestial sphere.

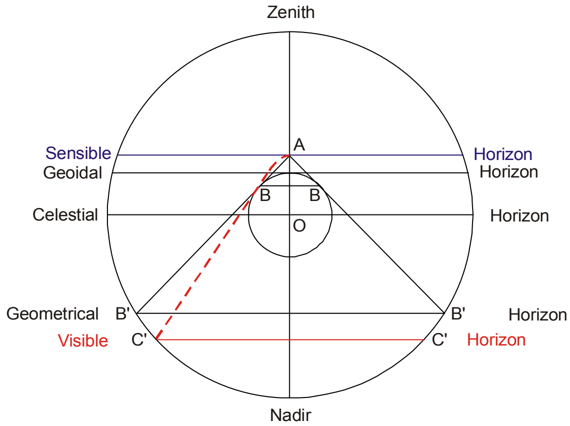
Gravity - The force of attraction between two bodies generated by their masses.

Great Circle - A circle that bisects a sphere. The celestial equator and ecliptic are examples of great circles.

Horizon –

> **Celestial Horizon** - The celestial horizon is a great circle on the celestial sphere whose plane lies at 90° to the zenith/nadir axis of an observer and passes through the centre of both the Earth and the celestial sphere.
>
> **Visible or Apparent Horizon** - The line at which the Earth and sky appear to meet is called the visible or apparent horizon. Although, on land, this is usually an irregular line, at sea, the visible horizon appears very regular. Its position relative to the celestial sphere depends primarily upon the refractive index of the air and the height of the observer's eye above the surface.

Geoidal/Sensible Horizon - If the plane of the horizon forms a tangent to the Earth it is called the geoidal horizon and if it passes through the eye of the observer (A) it is the sensible horizon.



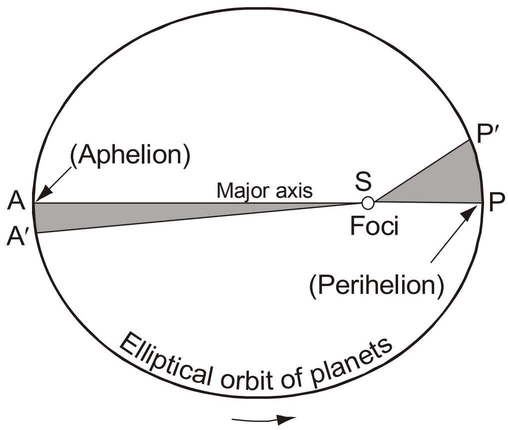
Inclination - The tilt of the rotation axis or orbital plane of a body.

Kepler's Laws - Kepler defined the following laws of planetary motion:

a. The orbit of each planet is an ellipse, with the Sun at one of the foci.

b. The line joining the planet to the Sun sweeps across equal areas in equal times.

c. The square of the sidereal period of a planet is proportional to the cube of its mean distance from the Sun.



Latitude - The angular distance of a point north or south of the equator of a body as measured by a hypothetical observer at the center of a body.

Local Hour Angle - The angle, measured westward around the celestial equator, between the meridian and the point on the equator nearest a particular celestial object.

Longitude - The angular distance around the equator of a body from a zero point to the place on the equator nearest a particular point as measured by a hypothetical observer at the center of a body.

Major Axis - The axis of an ellipse that passes through both foci. The major axis is the longest straight line that can be drawn inside an ellipse.

Mean Solar Time - Time kept according to the average length of the solar day.

Meridian - The great circle passing through an observer's zenith and the north and south celestial poles.

Moon – Phases

Crescent Phase - The phase of the moon at which only a small, crescent-shaped portion of the near side of the Moon is illuminated by sunlight. Crescent phase occurs just before and after new moon.

Full Phase - The phase of the moon at which the bright side of the Moon is the face turned toward the Earth.

New Phase - The phase of the moon in which none or almost none of the near side of the Moon is illuminated by sunlight, so the near side appears dark.

Quarter phase - The phase of the moon in which half of the near side of the Moon is illuminated by the Sun.

Waning Crescent - The Moon's crescent phase that occurs just before new moon.

Waxing Crescent - The Moon's crescent phase that occurs just after new moon.

Minute of Arc - A unit of angular measurement equal to 1/60 of a degree.

Nadir - The nadir is the point on the celestial sphere diametrically opposite the zenith.

Nodes - The points in the orbit of the Moon where the Moon crosses the ecliptic plane.

North Celestial Pole - The point above the Earth's north pole where the Earth's polar axis, if extended outward into space, would intersect the celestial sphere. The diurnal circles of stars in the northern hemisphere are centered on the north celestial pole.

Orbit - The elliptical or circular path followed by a body that is bound to another body by their mutual gravitational attraction.

Perigee - The point in the orbit of the Moon, planet or other artifical satellite nearest to the Earth.

Perihelion - The point in the orbit of a body when it is closest to the Sun.

Period - The time it takes for a regularly repeated process to repeat itself.

Perturbation - A deviation of the orbit of a solar system body from a perfect ellipse due to the gravitational attraction of one of the planets.

Precession - The slow, periodic conical motion of the rotation axis of the Earth or another rotating body.

Prime Meridian - The circle on the Earth's surface that runs from pole to pole through Greenwich, England. The zero point of longitude occurs where the prime meridian intersects the Earth's equator

Right Ascension - Angular distance of a body along the celestial equator from the vernal equinox eastward to the point on the equator nearest the body. Right ascension is analogous to longitude in the terrestrial coordinate system.

Sidereal Day - The length of time (23 hours, 56 minutes, 4.091 seconds) between successive appearances of a star on the meridian.

Sidereal Month - The length of time required for the Moon to return to the same apparent position among the stars.

Sidereal Period - The time it takes for a planet or satellite to complete one full orbit about the Sun or its parent planet.

South Celestial Pole - The point above the Earth's South Pole where the Earth's polar axis, if extended outward into space, would intersect the celestial sphere. The diurnal circles of stars in the southern hemisphere are centered on the south celestial pole.

Summer Solstice - The point on the ecliptic where the Sun's declination is most northerly. The time when the Sun is at the summer solstice, around June 21, marks the beginning of summer.

Synodic Month - The length of time (29.53 days) between successive occurrences of the same phase of the Moon.

Synodic Period - The length of time it takes a solar system body to return to the same configuration (opposition to opposition, for example) with respect to the Earth and the Sun.

Tropical Year - The interval of time, equal to 365.242 solar days, between successive appearances of the Sun at the vernal equinox.

Vernal Equinox - The point in the sky where the Sun appears to cross the celestial equator moving from south to north. This happens approximately on March 21.

Winter Solstice - The point on the ecliptic where the Sun has the most southerly declination. The time when the Sun is at the winter solstice, around December 22, marks the beginning of winter.

Year - The length of time required for the Earth to orbit the Sun.

Zenith - The point on the celestial sphere directly above an observer.

CHAPTER 13 - AERONAUTICAL DOCUMENTS

Contents **Page**

Introduction

1. The aim of this chapter is to summarize those aeronautical documents which have a direct application to the safe conduct of air navigation and which are available and relevant to the Services as a whole. The chapter does not include any discussion of documents that are promulgated by Commands or lower authorities.

2. Aeronautical information is published in a series of documents and charts known under the generic title of Flight Information Publications (FLIPs). Revised editions of most FLIPs take effect on certain pre-determined dates which accord with those agreed internationally under the Aeronautical Information Regulation and Control (AIRAC) system. The information published in FLIPs may be augmented or updated by Supplements to the UK Military Aeronautical Information Publication (UK Mil AIP) and Notices to Airmen (NOTAMs). Classified information is not published in either FLIPs or NOTAMs. FLIPs are available via the No 1 Aeronautical Information Documents Unit (No 1 AIDU) website; https://www.aidu.mod.uk/MilfLIP/. The Military Flight Information Publications (MilFLIP) provides authorised customers with secure internet access to the complete AIDU catalogue. For MilFLIP access see para 19.

MOD AERONAUTICAL CHARTS

The Ministry of Defence Catalogue of Geographic Products (GSGS 5893)

3. The MOD Catalogue of Geographic Products (GSGS 5893) provides details of the principal series of topographical maps, air charts and digital geographic products that are required by the Army, the Royal Air Force and the Royal Navy. The catalogue is available in electronic format only, and is updated regularly.

4. For each series of maps or air charts, a coverage diagram depicts the geographical limits of both the series and of the individual sheets. A portion of a sheet is usually included as an example. Each map or chart series is further described under the following headings:

a. **Type**. This section gives the purpose of the series, e.g. "Topographical (Air), coloured, overprints".

b. **Format**. In addition to naming the map projection used, this section includes other details such as the standard parallels and the scale factor of the chart.

c. **Size**. This section states the physical size of individual charts.

d. **Characteristics**. This section gives details of the aeronautical information represented on the chart, and the base map used.

5. Moving Map Displays for aircraft are listed and detailed (including areas of coverage) within this catalogue.

Chart Amendment Document (CHAD)

6. **Chart Amendment Document**. The Chart Amendment Document (CHAD) is available on line via the AIDU website to inform all MOD flying units and other holders of the GSGS 5893 of:

a. Significant additions and corrections to be considered when using the current edition of published charts within the geographical areas defined in the CHAD.

b. Notices of special interest to MOD aeronautical chart users.

Chart Updating Manual (CHUM)

7. **Chart Updating Manual**. The Chart Updating Manual (CHUM) is available on line via the AIDU website and amends certain US and RAF charts (Low Flying Charts and the FLIP En Route Charts are excluded from the CHAD/CHUM coverage.

Chart Amendments - Low Flying (CALF)

8. The Chart Amendment–Low Flying (CALF) provides an amendment service for the Low Flying Charts (LFC) and M5219-Air paper charts. Incorporated in the CALF is the Low Flying Supplement, containing the operating hours of scheduled airspace within the coverage of the Low Flying Charts. The CALF is available as a paper booklet or download from the AIDU website.

THE UNITED KINGDOM AERONAUTICAL INFORMATION SERVICE

9. The United Kingdom Aeronautical Information Service (UK AIS) is part of National Air Traffic Services (NATS) Ltd, and is located close to London Heathrow Airport. UK AIS is responsible for the collection and dissemination of information necessary for the safety, regularity and efficiency of air navigation throughout UK airspace. Details of UK AIS services and products can be obtained from the AIS website at http://www.nats-uk.ead-it.com/public/index.php.html .

The AIRAC System

10. The Aeronautical Information Regulation and Control (AIRAC) system gives a framework for planned changes to aeronautical facilities, procedures and regulations. A series of pre-determined dates (known as AIRAC dates) is published in advance. Changes will normally be planned to take effect on these AIRAC dates. Thus, with reasonable notice (normally 28 days), all operators can be made aware of any forthcoming change and its effective date.

The UK Integrated Aeronautical Information Package

11. The UK AIS produces aeronautical information in several publication formats, under the generic title of 'The UK Integrated Aeronautical Information Package (UKIAIP)'. Details of the UKIAIP can be obtained from the AIS website. The UKIAIP consists of:

a. **The UK Aeronautical Information Publication (UK AIP)**. The UK AIP contains information essential to air navigation and operations within UK airspace. The UK AIP can be accessed via the AIS website.

b. **UK AIP Supplements**. UK AIP Supplements detail temporary changes to the UK AIP, usually of long duration, and contain comprehensive text and/or graphics.

c. **Aeronautical Information Circulars (AICs)**. AICs are notices relating to safety, navigation, technical, administrative or legal matters.

d. **NOTAMs**. NOTAMs are notices relating to the condition or change to any facility, service or procedure notified within the UK AIP.

e. **Pre-flight Information Bulletins (PIBs)**. PIBs are summaries of the current status of aeronautical facilities and services and are available on the AIS website. They are produced for pre-selected areas, with almost world-wide coverage, and contain edited versions of selected NOTAMs. PIBs are issued as general bulletins containing route, aerodrome and general information, and also as navigation warning bulletins.

Notices to Airmen (NOTAMs)

12. A NOTAM is a notice containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations. Trigger MOTAMs are used to inform users of operationally significant information due to be incorporated in an AIP amendment or SUP. NOTAMs are available from the AIS website.

13. The existence of a NOTAM advising of an activity within an area does not grant the sponsor sole use of the airspace concerned, but simply advises other airspace users of the activity.

14. A NOTAM will deal with one subject only, and is originated by the unit where the change occurs. NOTAMs should be restricted to information of a temporary nature and of short duration, but may also be used when operationally significant permanent changes, or temporary changes of long duration, are made at short notice.

15. **The NOTAM Code**. Details of the NOTAM Code, its format and use are contained in the UK Mil AIP and in the Flight Information Handbook (FIH).

16. **The UK NOTAM Service**. The UK International NOTAM Office is a combined military and civil organisation within NATS and is part of the UK AIS. AIS Heathrow distributes NOTAMs to military units in accordance with distributions lists laid down by MOD. Low Flying Operations Squadron (Ops LF) based at RAF Wittering issue NOTAMs concerning the UK low flying system.

17. **NOTAM Display Boards**. NOTAMs are displayed in all RAF briefing rooms to facilitate easy reference to NOTAM information.

SNOWTAMs

18. A SNOWTAM is a specific type of NOTAM, used for notifying the presence or removal of hazardous conditions due to snow, slush, ice or standing water on the movement areas of aerodromes. The SNOWTAM proforma is explained in the UK Mil AIP and in the FIH.

MILITARY AERONAUTICAL INFORMATION SERVICES

No 1 Aeronautical Information Documents Unit (No 1 AIDU)

19. No 1 Aeronautical Information Documents Unit (No 1 AIDU) is responsible for the publication and distribution of all permanent unclassified information concerning any aeronautical facility, service, procedure or hazard, that might be required by UK military personnel directly involved with the operation and safety of aircraft. Most of this information is now provided in both hard copy and digital format. No 1 AIDU has a policy to migrate from the provision of paper based products to an electronic format where customers will download and print products locally. The AIDU website can be accessed via the web address in para 2. To access MilFLIP, a username and password is required which can be obtained by logging on to the AIDU website and selecting MilFLIP, where a request for a new account can be processed. This will allow the user to apply for access and for AIDU to verify the request. Deployed or diverted crews can obtain emergency access via AIDU Customer Services on telephone +44 (0) 8833 8587 or Mil 95233 8587.

20. AIDU FLIP publications may be considered in three groups:

a. Planning Documents and Services.

b. En Route Publications.

c. Terminal Area Documents.

Although produced primarily for the Armed Forces, most of these publications are available for purchase by civilian operators.

Planning Documents and Services

21. **The Integrated Aeronautical Information Package**. Planning information is published in the Integrated Aeronautical Information Package, which comprises:

a. The UK Military Aeronautical Information Publication (UK Mil AIP).

b. The UK Military Low Flying Handbook.

c. International Planning Information.

UK Military Aeronautical Information Publication (UK Mil AIP)

22. **The UK Military Aeronautical Information Publication (UK Mil AIP)**. The UK Mil AIP Consists of two volumes which are updated every 28 days by No 1 AIDU to meet the AIRAC schedule. The General and En-route volume (Volume 1) provides guidance to military aircrew on:

a. General Rules and Procedure.

b. ATS Airspace.

c. Radio Navigation Aids.

d. Warnings.

e. Military Training and Exercise Areas.

The UK Aerodromes volume (Volume 2) provides comprehensive information on UK military airfields including operating times, facilities, airfield surface and obstruction information, communications and runway lighting details, noise abatement and special procedures. It also contains graphics for SIDs and STARs, instrument approaches, airfield diagrams and ramp charts. The UK Mil AIP is produced every 28 days on CD ROM and is also available to download from the No 1 AIDU website.

23. **Amendments to the UK Mil AIP**. Amendments to the UK Mil AIP are issued once every 28 days, in the form of replacement sheets, to coincide with the AIRAC dates. The amendment is used to introduce permanent, operationally significant changes into the AIP on the indicated AIRAC date. These are issued in advance but do not become effective until the relevant AIRAC date.

24. **UK Mil AIP Supplements**. UK Mil AIP Supplements contain operational items of a temporary nature only. They are printed on yellow paper and normally issued every 28 days. The period of validity of the information will usually be given in the Supplement itself.

United Kingdom Low Flying Handbook (LFH)

25. **United Kingdom Low Flying Handbook**. This document is available for download from the AIDU website. It lists specific information regarding the Low Flying System and regulations, along with avoids, warnings and High Intensity Radio Transmission Areas (HIRTA).

a. **Section 1 The UK Low Flying System**. Section 1 contains a description of the low flying system along with general restrictions and procedures.

b. **Section 2 The UK Day Low Flying System**. Section 2 describes the day low flying system restrictions, Tactical Training Areas (TTA), TTA booking procedures and TTA timing restrictions.

c. **Section 3 The UK Night Low Flying System**. Section 3 contains the night low flying restrictions together with specific details for rotary wing operations.

d. **Section 4 The Highlands Restricted Area.** Section 4 gives details of the Highlands Restricted Area which is established to ensure the necessary traffic separation to enable Terrain Following Radar (TFR) training to be conducted in IMC.

e. **Section 5 Not Used.**

f. **Section 6 Centralised Aviation Data Service (CADS).** Section 6 contains details of the CADS system, the aim of which is to reduce the risk of mid-air collision.

26. **UK Low Flying Charts (LFC)**. The 1:500,000 LFCs and the M5219-A 1:250,000 series charts contain extensive Ordnance Survey topographical, obstruction and power line information in addition to portraying the Low Flying Areas and avoidances. The North and South Flag Officer Sea Training (FOST) 1:500,000 charts are designed for VFR low flying in the Plymouth Danger Areas.

27. **International Planning Information**. The International Planning Document that contained information on foreign airspace structure and national air traffic procedures is no longer available in print. This document has been replaced by a Library/Enquiry Service operated by the Aeronautical Information Bureau of No 1 AIDU. Enquiries can be made via telephone on DFTS 95233 8713 or civil 020 8833 8713. Some foreign AIPs are available via the AIDU website.

En-Route Publications

28. No 1 AIDU produces aeronautical information for use by aircrew in flight, in a series of conveniently sized publications. The coverage of RAF en route FLIPs is from the Eastern seaboard of the USA, through Europe, Africa, the Middle East and Southern Asia. British military users operating outside this area of coverage should use the appropriate FLIPs produced by the US Department of Defense, Canadian Forces or Royal Australian Air Force.

29. **The En-Route Supplement (ERS)**. The ERS is produced in four volumes, based on specified geographical areas (British Isles and North Atlantic (BINA), Northern Europe (NOREU), European and Mediterranean (EUMED), South Atlantic, Africa, Asia and Far East (SAAAFE)). Each ERS contains comprehensive details of aeronautical information and facilities within its specific area, including:

a. All active British military aerodromes, regardless of size.

b. Selected civil and other military aerodromes with a hard surface runway length of at least 5,000 ft, and some communications facilities.

c. Other aerodromes at the discretion of No 1 AIDU.

d. Relevant communications and navigational facilities.

30. **The Flight Information Handbook (FIH)**. The FIH is designed to provide a digest of information useful to aircrew during flight planning, and when airborne. It includes en route procedures, general planning information, emergency and safety procedures, codes and conversion tables.

31. **En Route Charts (ERCs)**. ERCs are available in both paper format and as downloads from the AIDU website. A sub-set of the charts is also available in digital format. ERCs provide details of ATS routes, designated airspace, airspace reservations, radio navigation facilities and en route communications. Due to chart congestion, sufficient information is given for transit flight only. ERCs should, therefore, always be used in conjunction with ERS, Planning Documents and Terminal

Publications. ERCs are drawn to plotting chart standards, based on the Oblique Mercator projection or the Lamberts Conformal projection. The latitude and longitude graticule on ERCs is based on WGS 84. Topographical data, other than major water features, is not shown. A Maximum Elevation Figure (MEF) is printed for each one degree quadrangle, where scale permits, for en route safety. The UK Mil AIP contains chart coverage diagrams together with an En-route Chart Legend, which is also available as a separate document. The following types of ERC are published:

a. **Low Altitude**. These charts portray aeronautical information within the vertical limits of each Flight Information Region (FIR), as stated on the chart panel.

b. **High Altitude**. Aeronautical information is shown only for the Upper Airspace. Where no Upper Flight Information Region (UIR) is defined, the lower limit of aeronautical information shown on the chart is FL 245. The true vertical limit of each FIR and UIR is shown on the chart panel.

c. **High/Low Altitude (H/L)**. These charts show aeronautical information for combined upper and lower airspace.

d. **Area Navigation (Rnav)**. Area navigation information is shown on charts which cover routes in the European area.

Terminal Area Documents

32. **Terminal Charts**. Terminal charts include Standard Instrument Departures (SIDs), Standard Arrival Routes (STARs), Terminal Approaches, Airfield Diagrams and Ramp Charts. A Terminal Charts Information and Legend leaflet is available in the UK Mil AIP Volume 1 or as a separate document. Terminal charts are available in various formats:

a. **Loose-leaf Format**. All TCs are available in loose-leaf format. The full list of current TCs is published in the Terminal Charts Specification and Legend. They are available for download from the AIDU website.

b. **Fast-Jet Terminal Chart Book**. A set of procedures (mostly TACAN and ILS) for airfields likely to be used by fast-jet aircraft is contained in the Fast-Jet Terminal Chart book which is produced every 56 days. Amendments are published in the Terminal Charts Amendment Bulletin (TCAB).

c. **Aerodrome Booklets**. These booklets contain TCs for airfields within a geographical area or route and are based on operational requirements.

d. **Terminal Charts UK North & South**. Volumes of terminal chart procedures to cover the UK are published in two volumes, North and South, separated by 52° 30’ N latitude. They have comprehensive coverage of all UK military airfields and include SIDs, STARs and airfield and ramp charts and are produced every 56 days. Significant amendments are published in the TCAB.

33. **Terminal Chart (TC) Specifications**. The majority of TCs made available through No 1 AIDU are produced by them, but some are purchased from the European Aeronautical Group (EAG) to cover gaps in the AIDU catalogue.

a. No 1 AIDU produce TCs known as No1 AIDU (RAF) New Specification charts. These charts use International Civil Aviation Organisation (ICAO) and UK AIP symbols and abbreviations. Exceptionally, abbreviations unique to AIDU are used. The symbols and abbreviations used on No1 AIDU (RAF) New Specification TCs can be found in the No1 AIDU Terminal Charts, Specification and Legend book. Some of the TCs listed in the Terminal Charts Catalogue (TCC) are the editorial responsibility of the EAG. AIDU is responsible for all military airfields and EAG, in general, for major international airfields.

b. The EAG produce TCs known as NAVTECH EAG charts. Symbols and abbreviations used on NAVTECH EAG TCs can be found in the NAVTECH Aerodromes Charts Specification and Legend book.

34. **Minor Aerodromes UK**. The Minor Aerodromes UK booklet contains information for selected aerodromes (Military, government and civil) in the UK that either do not have a published instrument let-down procedure, or do not meet the minimum criteria for inclusion in other FLIPs.

35. **Helicopter Landing Sites (HLS)**. Three HLS booklets are published, each containing detailed graphics and associated information for selected sites. They are supported by the TCAB. These booklets are titled:

a. Helicopter Landing Sites UK contains details of military and some civilian sites in the UK, together with helicopter routes in selected control zones and training areas.

b. Helicopter Landing Sites Hospitals UK contains details of hospital helicopter landing sites in the UK and certain control zones.

c. Helicopter Landing Sites and Visual Approach/Departure Charts – Europe contains military and some civilian sites in Belgium, Cyprus, Denmark, France, Germany, Italy, Norway, The Netherlands and Ireland along with associated visual approach and departure charts.

No 1 AIDU Amendment Services

36. FLIPs are amended by routine issue, and by an assortment of amendment bulletins, which form an integral part of all FLIPs. These amendments are produced and distributed in hard copy, and are also available via the AIDU website. The aeronautical information in FLIPs is also augmented and updated by NOTAM. The following amendment documents are issued:

a. **En-route Bulletin**. The En-route Bulletin is issued every 28 days contains amendments for ERC, ERS and the FIH. The ERB also contains ERC area of coverage.

b. **Terminal Charts Catalogue (TCC)**. All available Terminal Charts are listed in the TCC which is issued every 28 days.

c. **Terminal Charts Amendment Bulletin (TCAB)**. Non-permanent, textual amendments to the charts are published in the TCAB which is issued every 28 days.

d. **Terminal Documents Amendment Supplement (TDAS)**. The TDAS is published monthly on AIRAC dates. It supplements the Emergency and Unplanned Diversion Books (Vols 1-2), TC UK N & S and Fast-jet N & S. Only significant changes are published.

37. **Accuracy of FLIP Information**. All users of documents produced by No 1 AIDU, on finding an error or omission, have a responsibility for notifying No 1 AIDU without delay via AIDU Customer Services on telephone +44 (0) 8833 8587 or Mil 95233 8587.

38. **Accuracy of Aeronautical Charts**. Where errors are identified in aeronautical information on topographical charts (eg boundaries of controlled airspace) then, again, No 1 AIDU is to be informed. However, in the event that the error concerns the geographical base map (e.g. mapping details, including obstructions), then the point of contact is the Geo Support department at the Defence Geographic Centre, Feltham via +44 208 818 2726 or Mil (9)4641 4726.

No 1 AIDU Digital Products

39. **The Digital Aeronautical Flight Information File (DAFIF)**. DAFIF is the military standard for digital aeronautical data produced in support of Mission Planning, Flight Management Systems and Flight Simulation. It is administered by the National Geospatial Intelligence Agency and distributed to the MoD via No 1 AIDU.

40. **En-Route Charts (ERCs)**. ERCs provide graphical detail of airways routes, designated airspace, airspace reservations, radio navigation facilities and en-route communications. They are available in 1:500,000, 1:1,000,000, 1:2,000,000 and 1:5,000,000 scales.

41. **Low Flying Charts (LFCs)**. LFCs provide extensive topographical, obstruction, MEFs and powerline information in addition to providing all low flying information up to 2,000 ft, all other airspace up to 10,000 ft and generalised airspace up to FL 195. Available charts are the LFC UK (Day and Night), 1:5,000,000, and the North and South FOST 1:5,000,000.

42. **M5219 (Air) (aka Helicopter Charts)**. M5219 (Air) charts provide extensive topographical, obstruction, MEFs and powerline information in addition to providing all low flying information up to 2,000 ft, also depicting aeronautical information up to FL 100. They are available in 1:250,000 scale.

43. **Map Availability Catalogue (MAC)**. The MAC is available for download from the AIDU website only for each supported digital map system and type defining all mapping currently available to the AIDU customer.

CHAPTER 14 - NAVIGATION PLANNING

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Table of Figures

Introduction

1. The navigation planning requirements for any flight will depend largely on the nature of the task, the area of operation and any procedures or orders relevant to a particular aircraft type or role. Many tasks will be of a 'standard' nature, e.g. regular air transport routes, and, in such cases, maximum use can be made of Standard Operating Procedures (SOPs), computerized planning facilities and statistical meteorological data. Alternatively, the mission may be of an operational or emergency nature and the normal flight planning procedures may have to be amended or circumvented in the interests of expediency; much reliance will be placed on the use of SOPs and on the experience of the crew. It would be inappropriate to attempt to cover all of the specialist procedures in use; rather this chapter will review the basic navigation planning requirements for a straightforward flight at medium or high level. Fuel planning, which is an integral part of flight planning, will be covered in Volume 9, Chapter 15.

2. In order to highlight the principle ingredients of navigation planning, by way of example, this chapter will investigate the planning requirements and procedures for a straightforward flight from St Mawgan to Valley.

Pre-planning Considerations

3. Before any actual planning can take place a number of factors must be considered which will help to determine the route and techniques to be used. Among these factors are:

a. The task.

b. The fuel requirements or limitations.

c. Aircraft performance.

d. The geography of the area to be overflown.

e. The meteorological forecast for the route or area.

f. The availability and serviceability of navigation aids.

g. Air traffic control restrictions, danger areas and prohibited airspace.

h. Any special procedures that must be obeyed.

i. Availability of diversion airfields.

4. **The Task**. In this example, the task is straightforward; to navigate the aircraft safely between St Mawgan and Valley, in accordance with normal operating and air traffic procedures. It should be borne in mind, however, that frequently the task is more complex, eg there may be intermediate stops, specific times to make good at reporting points, air-to-air refuelling to be accomplished. The only restriction in this example is that the flight is to take place at cruising levels around FL 200.

5. **Fuel**. In this case, the flight is well within the capability of the aircraft with regards to fuel consumption. The detail of fuel planning is covered in Volume 9, Chapter 15.

6. **Aircraft Performance**. In this case, the aircraft has no performance limitations with respect to the cruising level, or with the runway lengths at either airfield. It should be noted that this is not always the case, for example, at some All-up Weights (AUWs) it may not be possible to climb to the desired level, and there may be prohibitive restrictions on runway length. On a short route, such as in this example, a major consideration is that, if the aircraft is fully fuelled at take-off, it may arrive at the destination, at an AUW which is too heavy for landing.

7. **Geography**. There are no particular geographical factors pertaining to this flight, except that it should be noted that the northern end of the route is over mountainous terrain and particular care must be taken when calculating safety altitude and when monitoring the descent.

8. **Meteorology**. The following meteorological data will be assumed:

a. **Cloud**. A general cloud base of 2,500 ft over the whole area, multi-layered up to tops at 15,000 ft.

b. **Wind**. The following wind structure applies to the whole route including departure and arrival airfields:

Surface	310°/15 kt
2,000 ft	315°/22 kt
5,000 ft	325°/30 kt
10,000 ft	330°/35 kt
20,000 ft	340°/45 kt
25,000 ft	350°/55 kt

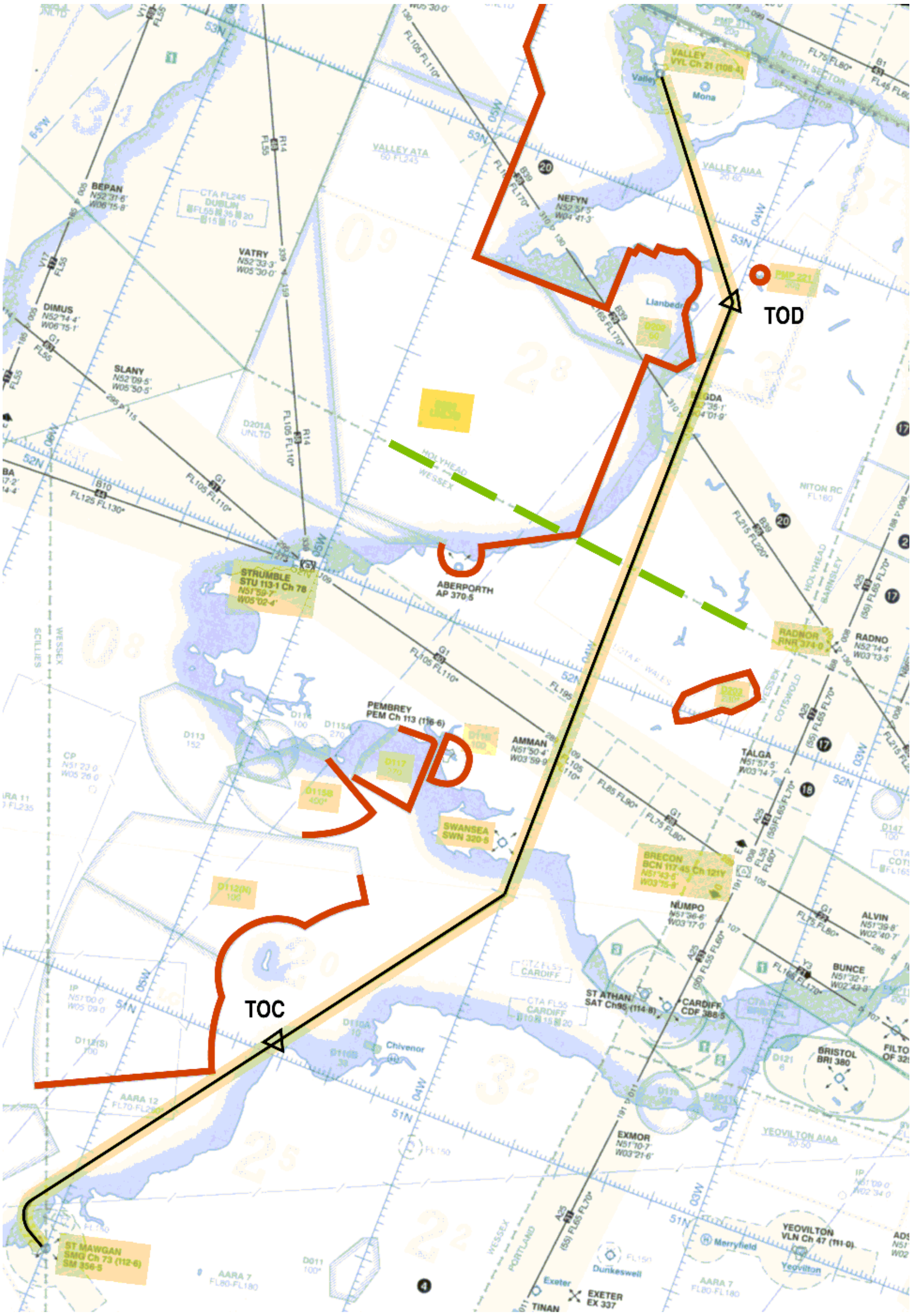
c. **Temperature**. The temperature is ISA +4.

d. **Weather**. There is no significant weather either en route or at either airfield.

9. **Navigation Aids**. It will be assumed that the aircraft is fitted with serviceable TACAN, VOR, ADF. All of the appropriate ground beacons are also serviceable.

10. **Restricted Airspace**. A study of the en route chart (Fig 1) reveals that there are a number of Danger Areas to be avoided, and some Airways to cross (for which clearance or control will be necessary).

9-14 Fig 1 En Route Chart for Route - St Mawgan to Valley (example only)



11. **Special Procedures**. Fig 2 shows the SID for St Mawgan, and it will be apparent that it involves no more than a climb on runway heading to 2,000 ft (QFE) before setting heading as required. The intention at Valley is to descend to the overhead at 1,000 ft, to join the visual circuit. These are simple procedures; however, particularly at major civilian airfields, the procedures are likely to be far more complex and will often influence the selection of the route to include specific reporting points. SIDs, STARs, the ERS, and the Planning Document will need to be consulted at the planning stage.