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DOCUMENT TITLE

ATPL NAVIGATION (AUS)

CHAPTER 6 – AIRWAYS NAVIGATION AND CHART PLOTTING

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INTRODUCTION

Navigation by means of formal plotting is best suited to situations in which a full-time navigator is carried on board an aircraft, and where navigation aids are few in number or non-existent. An appreciation of formal plotting processes does help in understanding the performance and limitations of radio navigation aids, and the operation of automatic navigation systems which have almost universally replaced the chart table in modern aircraft.

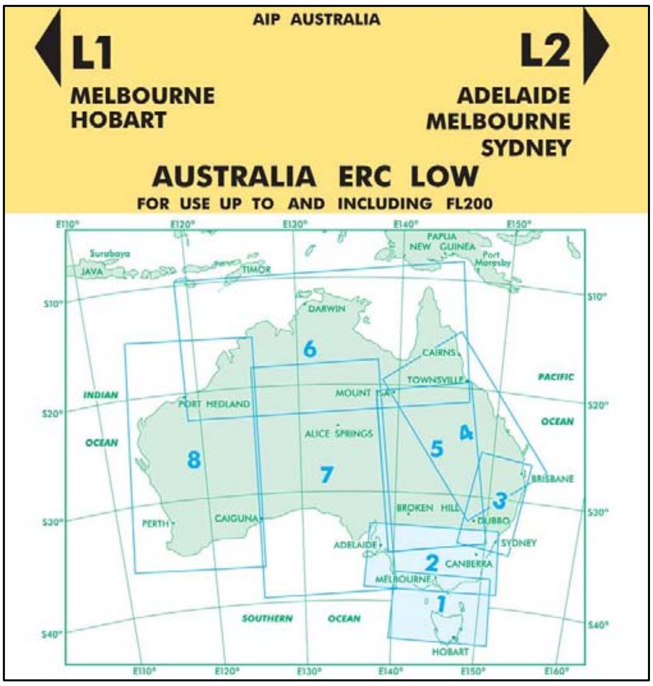


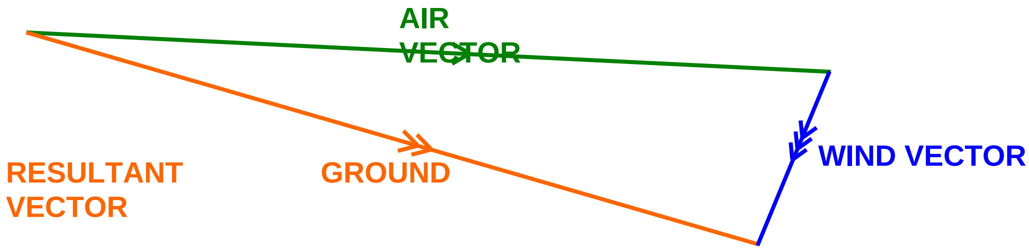
Figure 1

Now that we have the basic properties of Lambert's Conformal Conical Charts under control, we can look at utilising the charts for practical plotting. This will enable the keen pilot to verify his position in flight should he become geographically challenged, or to figure out wind direction and speed affecting the aircraft, although it would be more practical to do this on the CR-3 Navigation Computer. You could very likely expect questions in the examination that will test this aspect, so a basic knowledge regarding the use of en-route charts (ERCs) are required to be able to answer those.

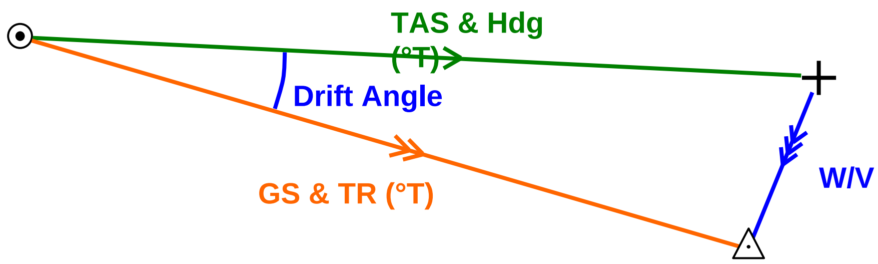
TRIANGLE OF VELOCITIES

Velocity is a speed in a given direction, and it may be drawn as a straight line whose length is proportional to speed, and its direction measured from a specific datum. In the navigational context, the datum will usually be a Meridian, or True North, but occasionally the datum could be Magnetic North, Grid North or some other arbitrary datum. The straight line is called a vector and three such vectors produce the triangle of velocities (vector triangle). True North is used as the datum in the following examples.

AIR VECTOR	**TRUE HEADING (direction)**	**TAS (magnitude)**
WIND VECTOR	**WIND DIRECTION**	**WIND SPEED**
GROUND VECTOR	**TRUE TRACK (direction)**	**GS (magnitude)**



NOTE: The arrows indicate the direction. Heading is the direction in which the aircraft is heading. W/V is the direction the wind is blowing from. The wind vector will always blow from the air to the ground vector. The ground vector is the resultant of the air and wind vectors, and is the direction in which the aircraft travels over the ground (track).



The wind vector ALWAYS blows FROM the air vector TO the ground vector. The drift angle is always measured FROM the air vector TO the ground vector.

DISTANCE AND DIRECTION

Basic plotting will involve drawing lines on an ERC, and measuring tracks and distances. Tracks and distances between waypoints on commonly used routes are published on the chart, but measurement might be necessary in some cases. In this regard, it is good to keep a few things in mind. From our knowledge on maps/charts we know that the meridians on our chart will give us the direction of True North. Although very useful, it would sometimes be easier if we could measure magnetic tracks directly, without first measuring a true track and then applying variation.

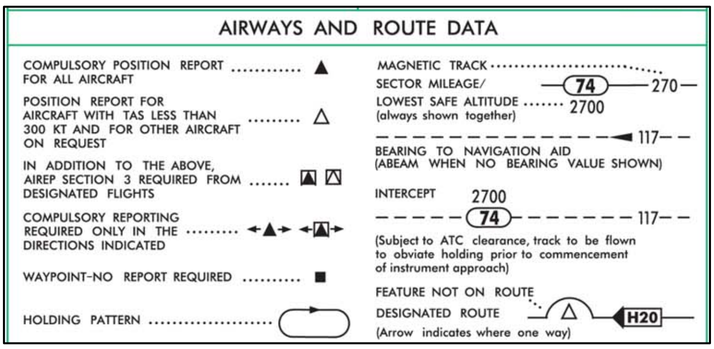
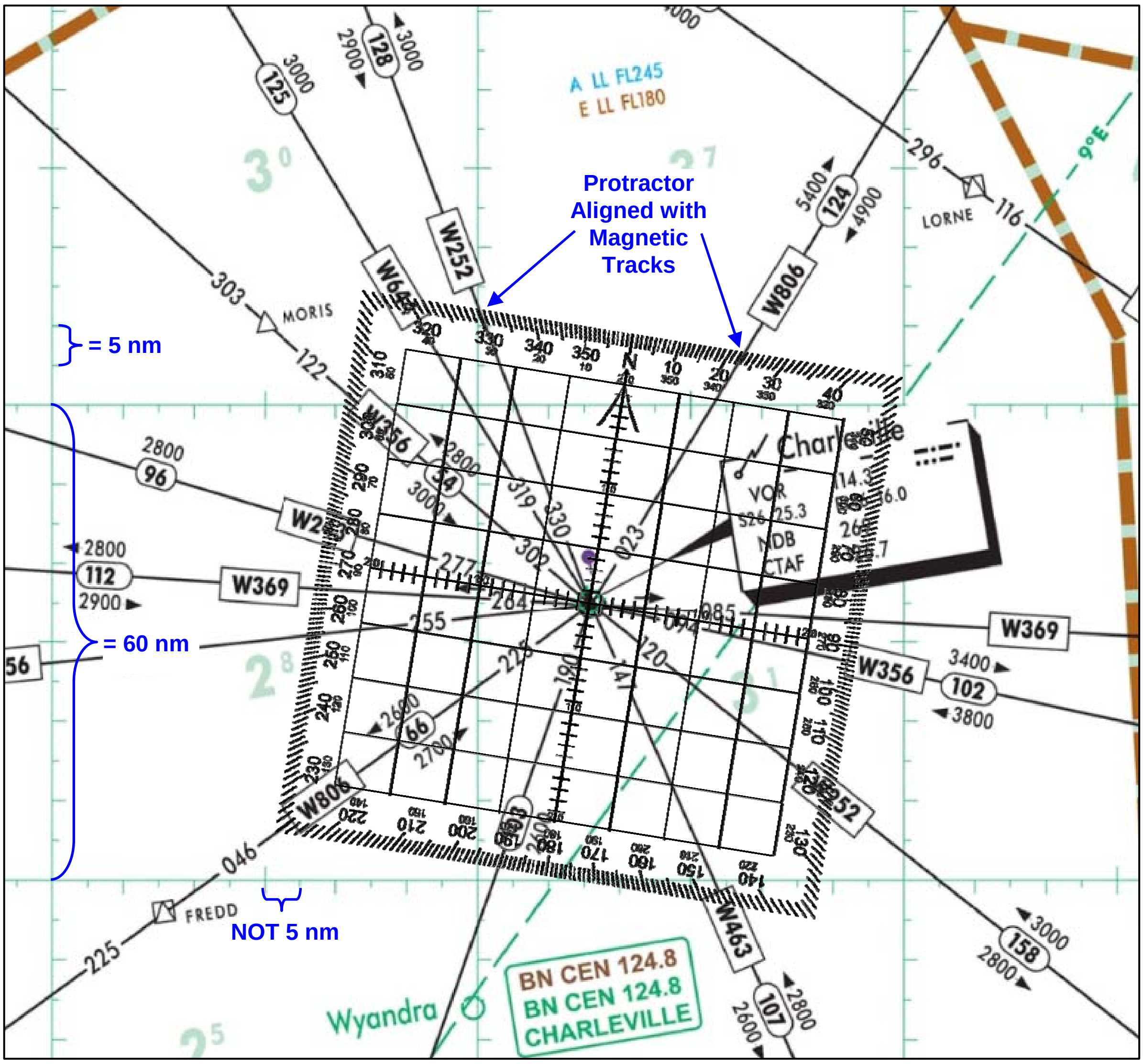


Figure 2

The track values published on an ERC are in °M, which facilitates easily alignment of a protractor with Magnetic North (see Figure 3). The published distances between waypoints are given in nautical miles (nm), but at times it will be required to measure the distance on a track which is not on a published route. For this, the linear distance scale provided on each ERC can be used.. All ERCs are not drawn to the same scale, so a navigation ruler cannot be used for distance measurement. A more accurate way of measuring distances accurately it to use the latitude scale as 1' of latitude is equal to 1 nm. The ERC Low series has latitude marks every 5 minutes, and this equates to 5 nm (Figure 3).

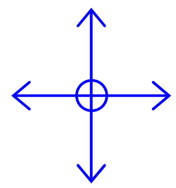
Utilising the latitude scale at the location where you are measuring will be quicker than rustling around trying to locate the linear scale. It will also be more accurate as the linear scale depicts an average scale and not necessarily the scale at your location on the chart. Using a set of dividers is a very convenient way of measuring distances against the latitude scale. Be very mindful not to measure against a longitude scale as 1' of longitude is only equal to 1 nm at the Equator. Also remember that the latitude scale is marked of north-south along a meridian, whereas the longitude scale is marked of east-west along a parallel of latitude.



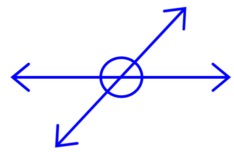
Figure

POSITION LINES

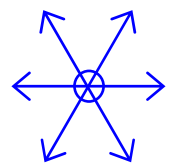
A position line is a line drawn on a chart passing through the aircraft's position. Position lines can be straight or curved, depending on the source of the position line. Obtaining two (or more) position lines at a common time and plotting these on the chart provides an intersection, and therefore a positive fix at the point of intersection. The position lines can be obtained from various sources (VOR, VDF, NDB, weather radar, and/or DME).



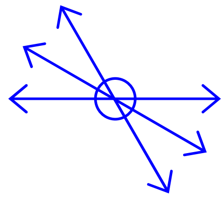
Two Position Line Fix (Ideal)



Two Position Line Fix

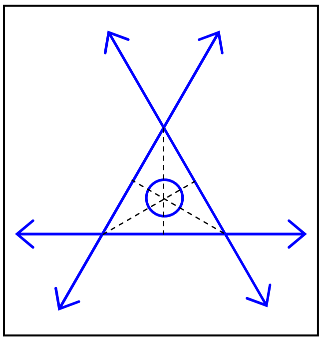


Three Position Line Fix (Ideal)



Three Position Line Fix (Acceptable)

When forming a fix, we must ensure an adequate angle of cut, so that minor errors in each position line do not result in a major error in the fix position. For two position line fixes, the angle of cut should, ideally, be 90°, although anything in excess of about 45° is acceptable in practice. The lines of a three position line fix should, ideally, cut at 120°, but in practice a minimum cut of 30° between any two of the position lines is acceptable (see diagrams to the right).



In the case of three position line fixes, it often happens that errors in the individual lines result in their failure to intersect at a point. We then obtain a 'cocked hat', as shown in below. If the expected band of error about each position line is similar, e.g. if all are ADF bearings taken over similar distances, the most likely fix position is the 'centre of mass' of the cocked hat. This is found by joining the mid-point of each side of the triangle with the vertex opposite, and accepting the intersection as the fix position (see left). For practical purposes if the cocked hat is relatively small you are able to estimate the middle of the triangle fairly accurately and can use that as the fix position.

In Australia, there are very specific rules with regard to position fixing from radio beacons and these have to be adhered to. In addition to the AIP extract on the right, the **theoretical** and **rated coverage** given in the AIP has to be considered.

ENR 1.1 - 38 **8 MAR 12** **AIP Australia**

19.5 **Position Fixing**

19.5.1 A positive radio fix is one determined by the passage of the aircraft over:

a. a NDB; or
b. a VOR station; or
c. a DME; or
d. is one determined by GNSS meeting the equipment and pilot requirements of GEN 1.5 Section 8.; or
e. is one determined by the intersection of two or more position lines which intersect with angles of not less than 45° and which are obtained from NDBs, VORs, localisers or DMEs in any combination.

For the purpose of this paragraph, a position line must be within the rated coverage of the aid with the exception that if a fix is determined entirely by position lines from NDBs, the position lines must be within a range of 30NM from each of the NDBs.

AIRWAYS NAVIGATION

Airways flying usually involves flight along fixed routes that are well covered by radio navigation aids. This means that position lines are readily available, almost always over ranges that are sufficiently short to render unnecessary any consideration of convergency or conversion angle. In these circumstances formal plotting is unnecessary.

Radio Navigation Aids makes the establishment of drift, TMG, groundspeed and heading to steer to destination fairly simple. It is also possible to find accurate spot winds very quickly, thus facilitating the task of pre-planning subsequent segments of the flight.

In this section we will investigate some of the techniques of airways navigation. Consideration will be limited to simple navigation aids that provide bearings e.g. ADF, VOR, and range, e.g. DME. Similarly, we will consider only basic cockpit displays, in particular the relative bearing indicator (RBI), the radio magnetic indicator (RMI), and simple readouts of DME range. The principles established using this most basic approach are generally applicable, and provide the foundation upon which modern techniques of radio navigation are based.

THE RELATIVE BEARING INDICATOR

DRIFT

Consider an aircraft that overflies an NDB and then maintains a constant heading while continuing to monitor the ADF needle on the relative bearing indicator. A short while later the needle is observed to take up a constant bearing in the vicinity of 180°R (relative). Suppose, for example, that this steady relative bearing is 190°.

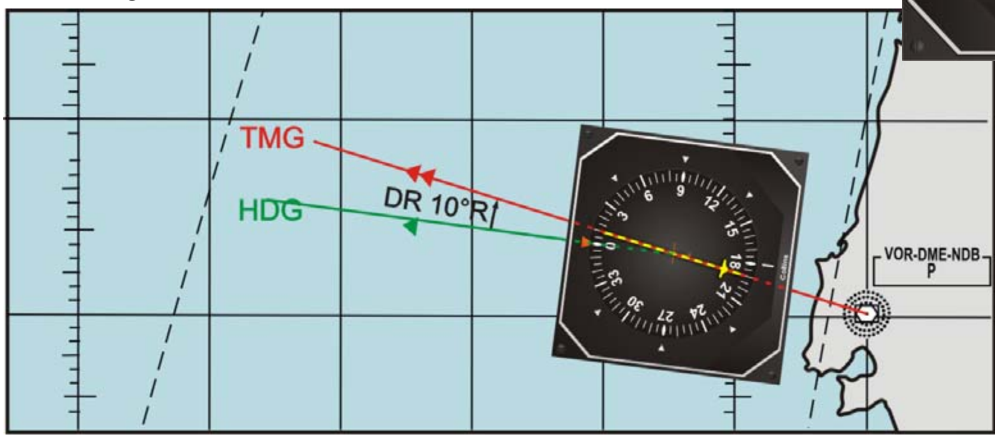


Figure 4

The ADF needle always points directly towards the NDB. As the aircraft overflew the NDB and has not since changed heading, the ADF needle is aligned with the TMG as shown in the plan view at Figure 4. The aircraft heading defines the zero relative bearing, and all other relative bearings are measured with respect to that datum.

Therefore, the reading of 190°R in the example must be associated with a heading/TMG combination as shown, from which we observe that the drift is 10°R.

Now consider the same situation, but with a steady relative bearing of 180°. See Figure 5.

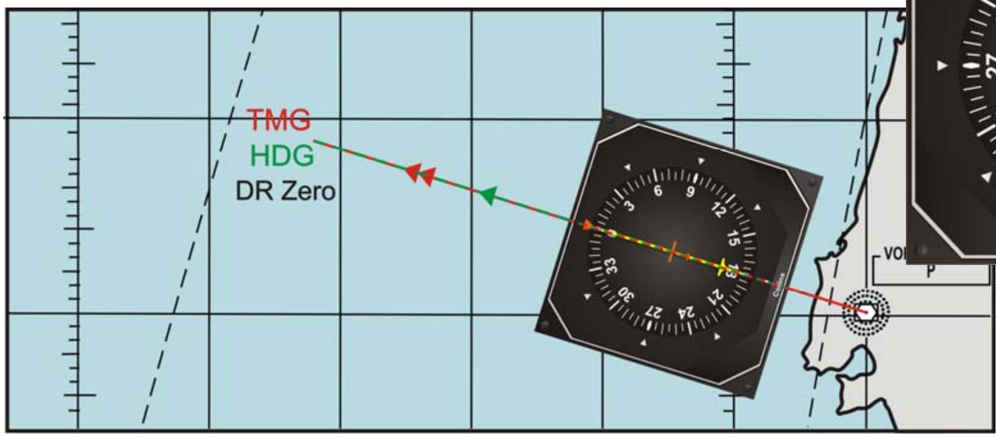


Figure 5

In this case the heading is aligned with TMG, so the drift experienced is zero.

Finally, consider a steady relative bearing of 170° as shown in Figure 6.

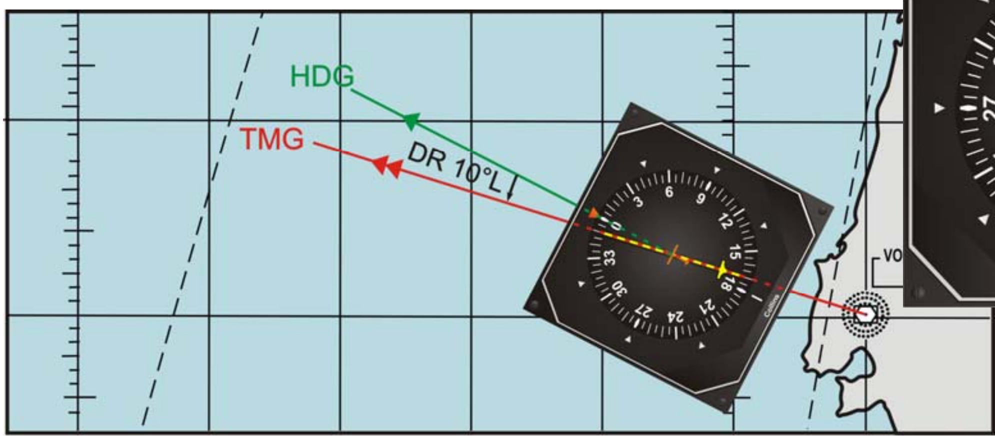


Figure 6

Here, the heading/TMG relationship is observed to be the opposite of that in Figure 4, i.e. the drift is now 10°L.

From these examples we deduce the following general rule of the utmost importance:

> When an aircraft overflies a beacon on a constant heading and subsequently observes the steady relative bearing back to the beacon, the drift affecting the aircraft is;
>
> - left if the RB < 180°
> - zero if the RB = 180°

- right if the RB > 180°,

and the magnitude of the drift is given by the angular difference between the observed relative bearing and 180°.

Hence, the RBI can be used as a drift meter, the only condition being that the aircraft must accurately overfly the NDB and then maintain heading while the relative bearing settles to its constant value. Note that the actual heading flown is of no consequence provided it is held constant; the technique will always give the actual drift experienced on that heading. Therefore, if a pilot had no idea of the actual drift, he need only fly flight plan track as heading over the NDB, and then simply read the drift from the RBI. Little time is taken to complete the procedure, so an adjustment to heading to parallel track could easily be completed before any significant track error had developed.

HEADING TO FLY

The procedure described above involves a beacon behind the aircraft. Usually the aim is to overfly the next beacon ahead of the aircraft so we need a method of finding a heading to achieve that result. In effect, we use the drift finding procedure in reverse; having found the drift steer the heading that makes the relative bearing indicator read the actual drift. For example, if the drift is 8°R, adjust the heading to obtain a relative bearing to the beacon of 8°R, or 008°R. If the drift is zero fly directly towards the beacon, (relative bearing zero), and if the drift is 15 °L, fly the heading that gives a bearing of 15°L, or -15°, or 345°R.

See figure 7, in which we have 15°L drift, and wish to overfly beacon X.

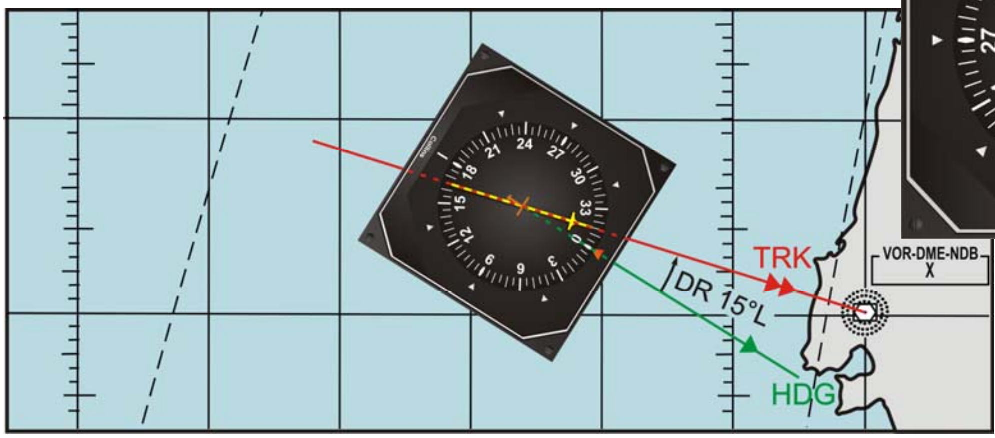


Figure 7

Again, note that the direction of approach towards X does not matter, provided we know what the actual drift is while flying on or near the required heading.

If the RBI has the capability to display bearings to two NDB's simultaneously, we can combine the results obtained in the preceding sections by tuning one ADF to the beacon behind the aircraft and the other ADF to the beacon ahead.

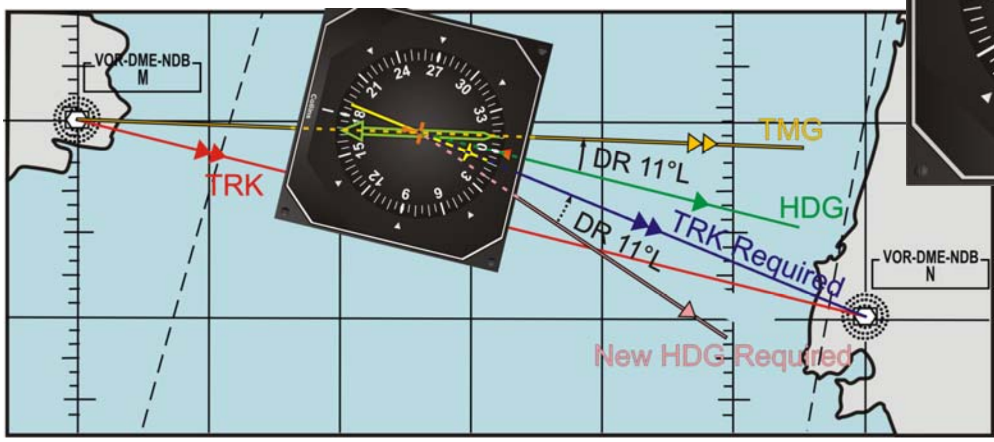


Figure 8

Suppose, for instance, the aircraft in figure 8 had allowed for zero drift between beacons M and N, but had actually experienced 11°L drift. Obviously, a track error of 11° would result. Equally obvious, the relative bearing to beacon N is not compatible with a successful homing to N under the influence of the actual drift. To achieve such a homing, we would have to turn the aircraft to the right until the needle pointing to N was in the 349°R position. The display might then appear as in figure 9.

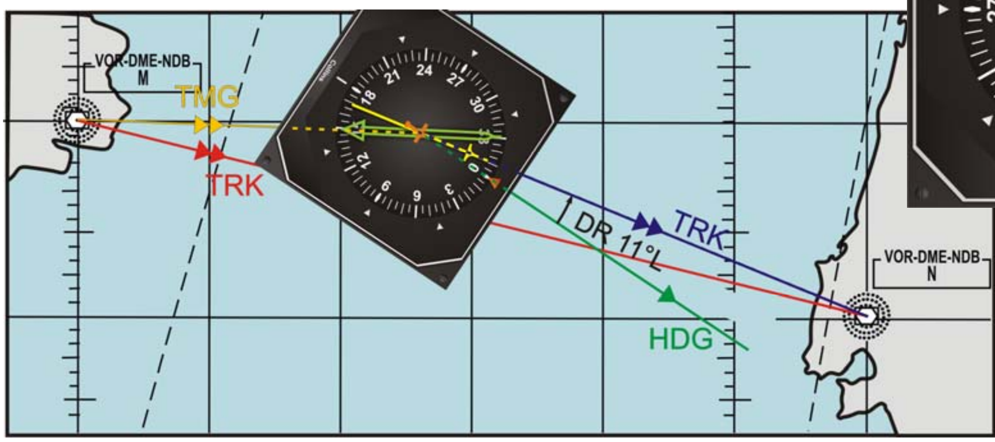


Figure 9

Subsequently, the relative bearing to beacon N (349°) would remain constant, but the bearing back to beacon M would slowly increase until, at the instant of overflying N, the bearing to M would be about 160°R.

From the foregoing we observe that, if the aircraft is on the straight line track between two beacons, and if the correct allowance for drift is made, the two needles on the dual RBI will be perfectly aligned. The needle pointing behind is offset from the 180°R position by an amount equal to drift, as is the needle pointing ahead offset from the zero position. It follows that if the needles are not perfectly aligned the aircraft cannot be on the direct track between the beacons, and if the aircraft is on track, the needles cannot be misaligned.

CROSS-TRACK BEARINGS

We have seen that the needle must be offset from the RBI zero datum by the amount of drift if a direct homing to a beacon ahead of the aircraft is to be achieved. The same is generally true of all bearings, in particular, those used to indicate when the aircraft is abeam the beacon. Position reporting points are often defined in this manner, so it is important that the relationship between the relative bearing and the abeam position be understood fully. Consider the diagrams at Figure 10. Both depict situations in which there is no drift, and it is clear that the relative bearings defining the abeam position in this special case will be 090° or 270° depending upon the location of the beacon with respect to track.

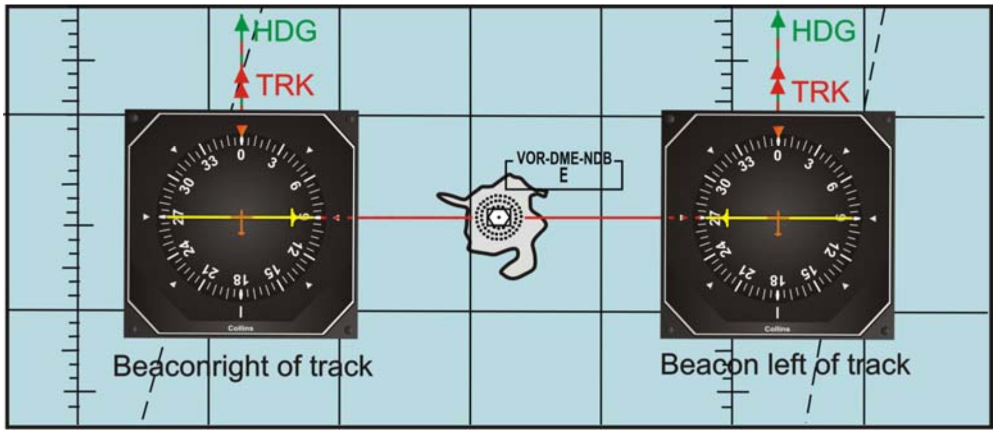


Figure 10

In figure 11 we show aircraft on the same tracks, but subject to 20°L drift. It is apparent that the relative bearings depicting the abeam positions are no longer 090/270 degrees, but are offset from those points by an angle equal to the drift.

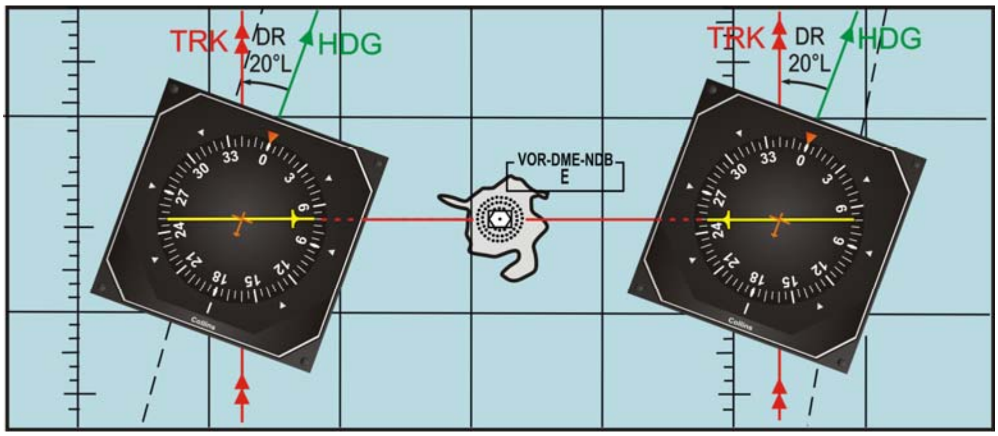


Figure 11

Furthermore, the direction of the offset behind or ahead of the aircraft's lateral axis is not fixed for a given direction of drift, but depends upon whether the aircraft passes to the right or left of the NDB. In figure 12 we show the same situation, but with 20°R drift. Note that the directions of offset from 090/270 are reversed in this case.

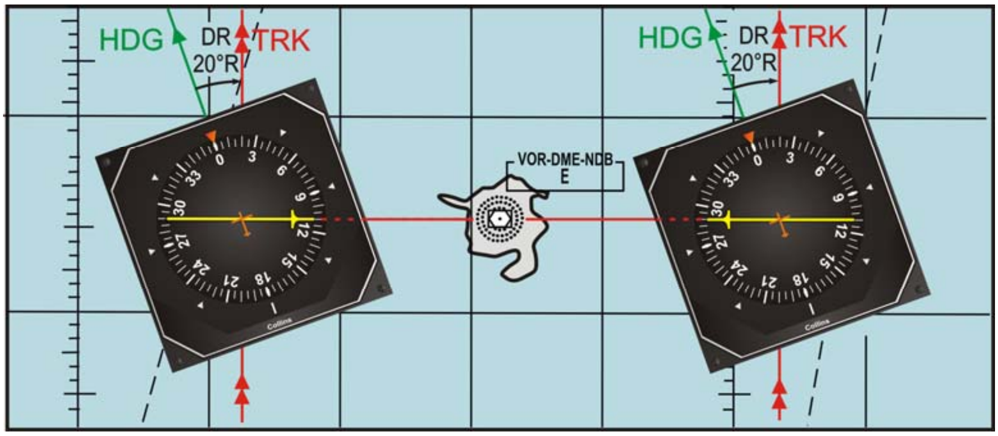


Figure 12

If the drift angle is large and the beacon is a significant distance off track, it is evident that a large error will result if the abeam position is called simply when the relative bearing reaches 090 or 270 degrees. Allowance must be made for drift, using the following rule derived from Figures 10, 11 and 12:

- with left drift, abeam relative bearing $<$ 090 or 270,
- with zero drift, abeam relative bearing = 090 or 270,
- with right drift, abeam relative bearing $>$ 090 or 270,

and the required angular displacement from 090 or 270 equals the magnitude of the drift.

THE RADIO MAGNETIC INDICATOR

From our previous consideration of the relative bearing indicator with two needles, it is a small step to the radio magnetic indicator (RMI).

The RMI differs from the RBI in only two significant areas:

1. The compass card is not fixed, but is driven by the aircraft compass system so that it always displays the aircraft magnetic heading at the top (12-o'clock) position.

2. The RMI always has two pointers, a narrow yellow one usually called 'needle number 1', and a broad green one usually called 'needle number 2'. The two pointers are often labelled accordingly. By means of selector switches (push button), the two pointers are assigned to display ADF or VOR information in any desired combination.

A typical display appears in figure 13, which shows an aircraft heading of 060°M, a VOR bearing of 040°(M) on the yellow number 1 needle and an ADF bearing of 100°(M) on the green number 2 needle.

Figure 13

Like the RBI, the RMI displays bearings in their correct relative position from the aircraft heading. But because the compass card itself rotates, the bearings read from the needles are no longer relative bearings but magnetic bearings. In effect the compass rotation has performed the calculation.

Brg(°M) = Hdg(°M) + Rel Brg,

leading to the direct display of magnetic bearing. Bearings are obtained from both the 'arrow head' and 'tail' of the needles as follows:

NAVAID	HEAD OF NEEDLE	TAIL OF NEEDLE
VOR	Brg(°M) to the beacon (QDM)	Radial (QDR)
ADF	Brg(°M) to the beacon (QDM)	Brg(°M) from the beacon (QDR)

Because of the different characteristics of the ADF and the VOR, and the internal design of the RMI, a compass failure will leave the instrument useable but with the following limitations:

1. The ADF will still show the correct relative direction to the NDB, but the magnetic bearing will be in error by the amount of compass error.
2. The VOR will still show the correct magnetic bearing to the beacon (and radial), but the relative direction to the beacon will be in error by the amount of the compass error.

We now consider how the RMI might be used to determine the heading to steer to a destination or turnpoint. In each case it is assumed that the instrument is used in conjunction with one VOR or ADF tuned to a beacon ahead of the aircraft, and one tuned to a beacon behind. The solution to the 'heading to steer' problem can be obtained using at least three different methods, although all rely upon the same basic principles. We use an example to demonstrate the application of each method.

Figure 14 depicts an aircraft that has maintained a heading of 090°(M) after overflying beacon X, and now requires to alter heading direct for beacon Y. The bearings obtained are shown on the diagram.

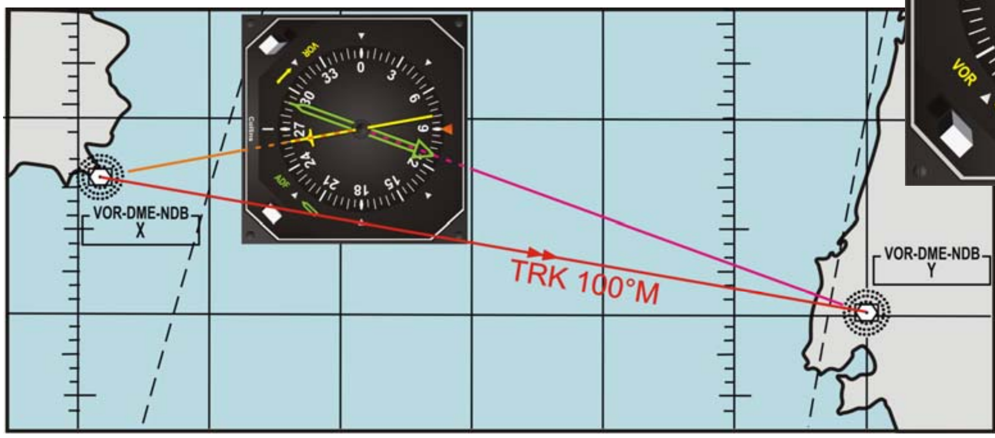


Figure 14

METHOD 1

This is the 'formal' solution to the problem.

Brg to X	=	260
∴ Brg from X	=	080
∴ TMG	=	080
Hdg(M)	=	090
∴ Drift	=	10L
Brg to Y	=	110
∴ Required track	=	110
∴ Required Hdg	=	120

METHOD 2

Method 2 uses the RMI as a drift meter as previously described for the RBI.

Hdg	=	090
∴ Reciprocal of Hdg	=	270

This point on the RMI scale is equivalent to the 180° relative point on the RBI.

Brg to X	=	260,
∴ Drift	=	10°L

ie. 10 degrees less than the reciprocal of the Hdg

From this point proceed as in Method 1 to obtain the required heading of 120(°M).

METHOD 3

This is the ‘track error + closing angle’ solution. It uses the properties of the RMI fully, and provides the quickest and easiest solution to the problem.

Observe from figure 14 that the tail of the needle that points to the beacon behind the aircraft defines the TMG, and the head of the needle that points to the beacon ahead defines the track required, ie.

TMG	=	080
Required track	=	110

The difference between TMG and required track is, of course, the heading alteration required. It is also equal to TE + CA. Therefore, we simply alter heading towards the needle pointing ahead, by an amount equal to the angular difference between the needles, in this case 30 degrees to the right, ie.

Required heading	=	current heading + 30 degrees
	=	090 + 30 degrees
	=	120(°M), as previously determined

Note that this, and the other methods, all depend upon an implicit assumption that;

Heading alteration	=	Track alteration

This assumption is likely to be accurate if the angles involved are small. In the example used above the angles are not small, because the drift originally assumed was 10°R, and the drift actually experienced was 10°L, leading to a large track error. Nevertheless, even in these rather extreme conditions the error would be small, and a heading alteration as suggested would provide an outcome vastly better than would result from perseverance with the erroneous flight plan.

WIND FINDING

You might not always be flying an aircraft equipped with a fancy navigation system, or this fancy system might one day fail during flight. One of the factors that make aerial navigation difficult is the wind influence. Without any wind influence, the heading of the aircraft will also be its track, and the TAS will also be the ground speed. In flight this situation will arise rarely, if ever. We therefore need to take the influence of the wind into consideration. In our pre-flight planning we use the forecast W/V to determine what heading to fly to maintain a specific track, and what ground speed will be achieved. Meteorology is not always an exact science and as you might have experienced, sometimes the actual W/V experienced is a little bit different to the forecast W/V, necessitating corrections in flight to compensate for this change in W/V. This can only be done if you know what W/V is affecting the aircraft in flight.

When combined with a DME system selected to a beacon ahead or behind the aircraft, either the RBI or the RMI provides a very rapid means of wind finding.

To find the spot wind we require knowledge of heading, drift, TAS and groundspeed.

- Heading is read directly from the compass (corrected for variation if true wind direction is required).
- Drift is found as described from the RBI or RMI.
- TAS is tabulated in the performance manual, or calculated directly from the aircraft instrumentation.
- Groundspeed is found from the DME.

Some DME's incorporate 'rate of closure' displays that provide a close approximation of groundspeed if a beacon directly ahead or behind the aircraft is used. In the absence of such a display, groundspeed is obtained by finding the distance travelled in a short period of time, typically three minutes. The technique relies upon the great accuracy of the DME, and on the ability to read the display to within a small fraction of one nautical mile. Two methods are available as follows.

1. If a precise readout of instantaneous range is available - as is the case with most DME systems - simply find the distance travelled in a fixed period of time, e.g.

12.75nm in 3 minutes $\therefore$ Groundspeed = 255 knots.

2. If using a less precise range readout, such as the range markers on the weather radar, it is preferable to time the passage of a return between two well defined ranges, eg. the 40nm and 30nm range markers, using a stopwatch, eg.

10nm in 2 minutes 21 seconds, i.e. 10nm in 141 seconds.

$\therefore$ Groundspeed = 255 knots, as above.

Note that Method 2 requires the setting of 10 on the distance scale of the computer against 141 on the time scale, and reading the groundspeed against '36' on the time scale:

i.e. 10nm in 141 seconds $\equiv$ 'x'nm in 3600 seconds.

where x is 255 in this case.

Some computers, including the Jeppesen CR2, have a small 'seconds' arrow at the '36' position for this purpose.
Having found the groundspeed, the spot wind is easily obtained from the navigation computer using standard techniques, ie:

WIND FINDING ON JEPPESEN CR COMPUTER

See the chapter on the Navigation Computer to refresh on the calculation of wind velocity on the Jeppesen CR series Navigation Computer.

WIND FINDING BY PLOTTING

In an examination question you could also be expected to calculate the W/V given two fix positions. There are two ways to calculate the W/V. Drawing on our knowledge of the navigation computer, if we have any four components of the triangle of velocities, the missing two can be calculated. If the TAS, Hdg, TR, and GS are known, the W/V can be calculated. To do this on the navigation computer, you need to measure the track and distance between the two fixes and calculate the GS from distance and time. Follow the steps described in the previous heading to calculate the wind on the Navigation Computer.

Alternatively this can also be solved easily on the chart by plotting the Hdg and TAS of the aircraft for the time period between the two fixes. The difference between the Hdg/TAS vector (air vector), and the TR/GS vector (track vector) is the W/V. This will be the wind influence for the time between the two fixes, so the wind speed must be calculated for one hour.

Example: Refer ERC L5 chart in figure 15 on the next page. The aircraft is tracking from Dubbo (S32°13.3 E148°34.6) to Charleville (S26°25.4 E146°15.9), via Walgett VOR (S30°01.8 E148°07.6).

1500Z Overhead Walgett VOR, CAS 220 kts, FL160, TAT-10°C

1530Z Heading 318°M, R330 Walgett VOR, Cunnamulla NDB (S28°02.4 E145°37.3) bearing 313° Relative

Assuming a constant heading of 318°M was held between 1500Z and 1530Z, the average wind that has affected the flight during this time is closest to?

Solution: Use the following steps and refer to Figure 5.

1. Plot the 1500 position overhead Walgett VOR.
2. Plot the 1530 position fix.
   a. With the protractor centred on Walgett VOR and aligned with the outbound track of 325°M, plot R330 *FROM* Walgett VOR. The aircraft is on this radial.
   b. Plot the bearing of 091°M *FROM* Cunnamulla NDB.

      (Hdg 318°M + 313°R = 271°M *TO* the NDB)
   c. The line between the 1500 and 1530 positions represents the aircraft TMG of 330°M, and the distance is the GS for 30 minutes.
3. Plot the aircraft Hdg 318°M and TAS for 30 minutes – 138.5nm.

   (TAS from CR-3 = 277 kts → 138.5nm)
4. Join the end of the Hdg/TAS vector and TR/GS vector. This represents the wind direction correctly in °M, but the length is for 30 minutes. The length is 38nm in 30 minutes, so the wind speed 76 kts. Place the protractor over the wind vector, lining it up with the track of 326°M/146°M. The wind direction is 283°M (wind always blowing the aircraft downwind of the Hdg onto the TR).

W/V 283°M/76

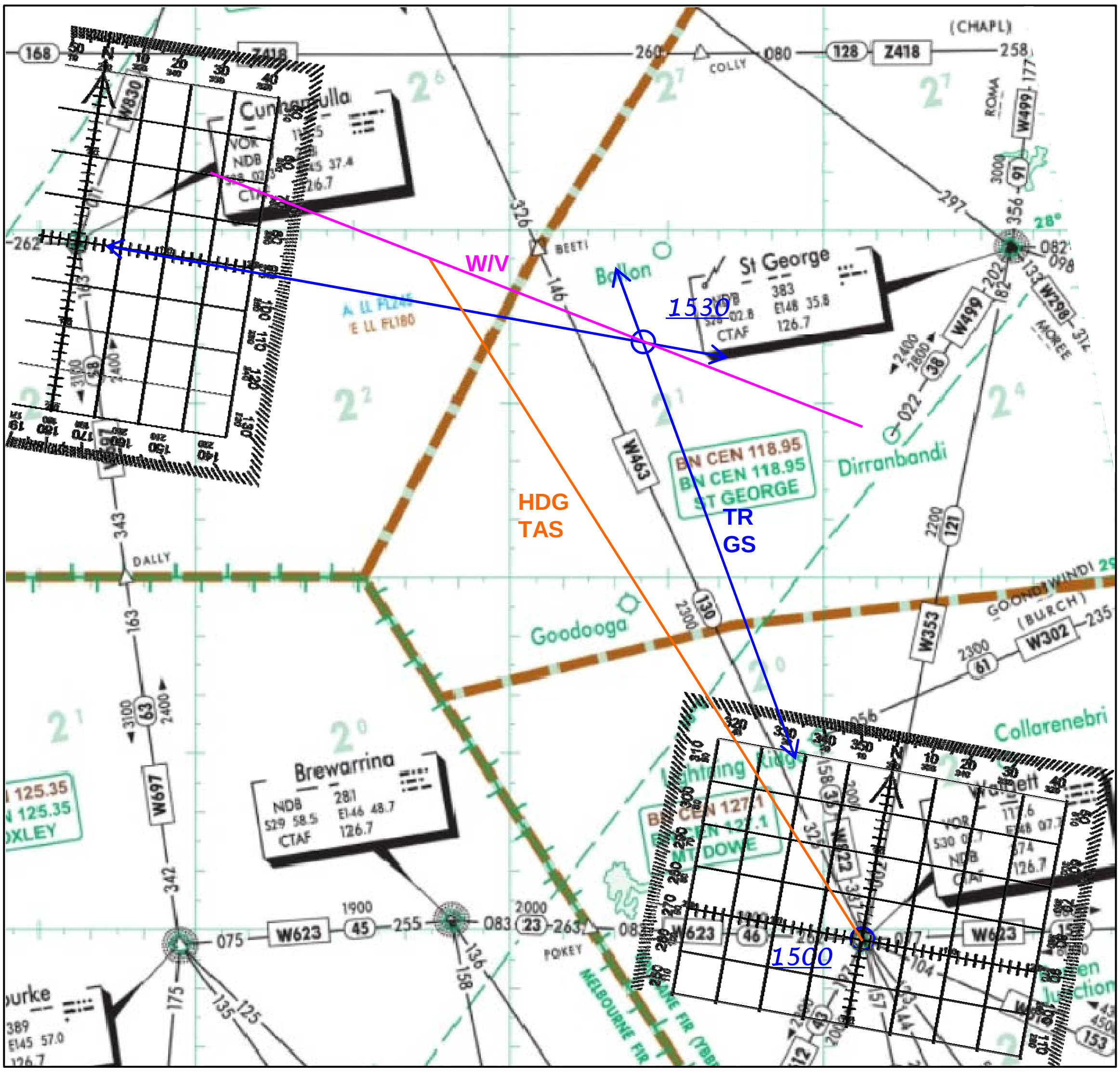


Figure 15

In an examination setting you could be required to calculate the TR and GS of the aircraft, or various other combinations. This serves only as a very basic introduction to plotting on a radio navigation chart. Through practice of these simple techniques the average pilot will be quickly able to pinpoint his position on the chart and make basic calculations for track corrections.

PLOTTING BEARINGS AND DISTANCES

As discussed above, you may be required to measure and/or plot distances and tracks which are not published on the chart. You may need to plot a bearing and distance from a radio beacon to determine the aircraft position. On most maps we convert radio bearings into °T from the station and then align the protractor with True North.

As the ERC already displays magnetic tracks from the radio beacons, it is much more convenient to simply align the protractor with these magnetic tracks and to then plot the bearing from the beacon in °M. It is then a simple process to draw in a line corresponding to this bearing from the beacon, and to mark off an arc corresponding to the DME distance obtained at the same time.

Radial 025 is obtained from Griffith VOR at 1036. This does not provide a fix, as we only know the aircraft is somewhere on R025 from Griffith. If we obtained a position line (bearing) from another beacon at the same time, we can fix the position of the aircraft. Alternatively, obtaining a range from a co-located DME at the same time still enables you to fix the aircraft position. In the example, at 1036, Radial 025 at a distance of 40nm was observed from Griffith, and then plotted on the chart (figure 16). Take note of the annotation of a time next to the position. Without noting the time next to the position, it becomes useless information as we need to know at what time the aircraft was at that particular position.

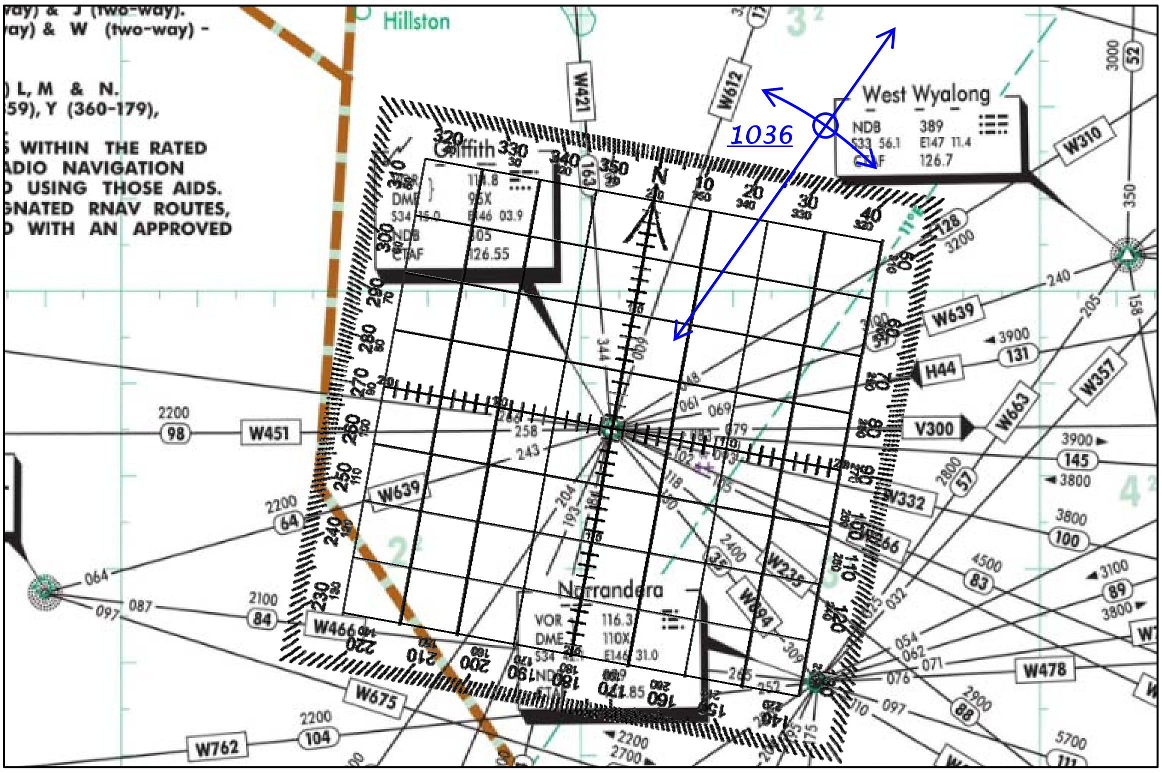


Figure 16