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air cadet publication
ACP 32

navigation
volume 3 - air navigation



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ACP 32

NAVIGATION

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Volume 3

Air Navigation

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Instructors' Guide

CHAPTER 1

DISTANCE/SPEED/TIME

Introduction

1. Aircrew will always need to know how long it will take for an aircraft to fly from A to B, maybe just to deliver passengers or payload on time but also because aircraft, unlike cars, cannot afford to run out of fuel. Regular checks have to be made that the time of arrival will occur before the fuel has all been used. To do this, it is necessary to know how far the aircraft has left to fly and how fast it is going over the ground.

Distance On The Earth

The nautical mile

2. Although the Earth is not perfectly round, we users of maps can safely assume that the Earth is a sphere. In ACP 32 Volume 1 we learned that the Latitude/Longitude grid divides the surface of the Earth into degrees and minutes. One minute of latitude represents one nautical mile (nm) and 1 degree of latitude (60 minutes) equals 60nm. As a complete circle is 360° , the 360×60 gives the circumference of the Earth as 21600 nm (approx 25000 statute miles). Notice that on nautical maps or charts there are no scales on the borders, so we have to use the nm scale which is shown along each meridian. Note also that the scale along the parallels is not used because convergence shrinks the scale considerably in the British latitudes, and even more near the Poles.

Scales on parallels are not used

Fig 1-1 RAF enroute chart



Find the distance between 2 places

3. In the example at fig 1-1, measure the distance between Shawbury and Birmingham, using the nm scale printed on the 002° West Meridian. This can be done with a ruler, a pair of dividers, or if you do not have any equipment, using the marks along the edge of any piece of paper.

Change of Latitude

Distance between places on the same meridian

4. If two places are on the same meridian then it is possible to calculate the distance between them rather than having to measure it; this is much simpler if several map sheets are involved. For example Torrejon airfield (near Madrid in Spain) is due south of RAF St Athan. These two latitudes are N40°29' and N51°24'. Subtracting one latitude from the other gives a change of latitude of 10°55'. Multiply 10° by 60 and add 55' to find that Torrejon and St Athan are 655nm apart. However, very few air journeys are made along meridians so to find out how far apart other airfields are, we either have to measure the distance on a suitable small-scale chart or allow our navigational computer to do the calculation for us using spherical trigonometry.

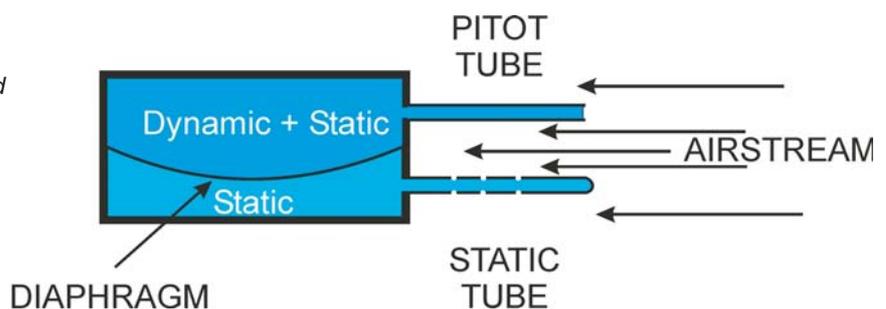
Aircraft Speed

Units of speed

5. We measure the speed of land-based vehicles (eg cars, bicycles) in miles per hour (mph). In aviation, as we use nm to measure distances, it follows that speed is measured in nm per hour (known as knots from the days of sailing ships). The other difference from land-based vehicles is that aircraft are not on the ground, the speed of rotation of the wheels cannot be used to drive a speedometer. As the aircraft flies through the air, we use an instrument called an Air Speed Indicator (ASI) to measure the "Dynamic Pressure" which is the pressure caused by the forward motion of the aircraft. We achieve this by measuring the difference between the pressure of the air surrounding the aircraft (atmospheric or "Static Pressure") and the pressure of the air captured in the Pitot Tube ("Pitot Pressure"), which is made up of static and dynamic pressure.

Air speed indicator

Fig 1-2 A Simplified Speed Indicator



A simplified ASI is shown in the diagram at fig 1-2. In forward flight the pressure above the diaphragm will consist of dynamic and static pressure whilst the pressure below is purely static pressure. The two static pressures cancel out and the diaphragm will move due to the dynamic pressure, the movement is amplified and displayed on the instrument as Indicated Air Speed (IAS), reading in knots.

Corrections

6. The reading on the ASI can be in error because of two errors, namely Pressure Error and Instrument Pressure. Pressure Error previously known as position is caused by sensing incorrect values of static pressure due to the position of the static vents relative to the airflow around the aircraft. Instrument error is caused by poor manufacturing tolerances when the instrument was built. Both errors can be measured by testing the aircraft under controlled conditions and a calibration card with the combined errors is displayed in the cockpit next to the instrument. Once the two errors have been accounted for, we are left with Calibrated Air Speed (CAS), formerly known as Rectified Air Speed (RAS).

$$\text{IAS} \pm \text{Pressure Error} \pm \text{Instrument Error} = \text{CAS}$$

Thus an IAS of 118 kts with a correction on the calibration card of +2 kts would give a CAS of 120 kts.

7. A pilot flies using Calibrated Air Speed because it represents the force of the airflow around the aircraft. The higher the aircraft flies, the less dense the air becomes and the faster the aircraft has to fly through the air to achieve the same force and therefore the same CAS. A navigator however, needs to know the actual speed that the air craft is flying through the air so that he can compare it with his speed over the ground and hence estimate the wind.

8. Therefore to obtain True Air Speed (TAS) from CAS you need to correct for air density changes caused by changes in temperature and altitude. This can be done either by calculation or by use of a navigation computer. In addition if you are flying at speeds greater than 300 kts, then you need to apply a correction for Compressibility Error, which is caused by air becoming compressed in the Pitot Tube.

$$\text{CAS} \pm \text{Density Error} + \text{Compressibility Error} = \text{TAS}$$

Units of Time**Which time do we use?**

9. Time is probably the only example of scientific measurement where every nation uses the same units. Everyone is familiar with days, hours and minutes; it is only necessary to ensure that you use hours when working with knots, as this speed is actually nautical miles per hour. In military and commercial aviation the 24 hour clock is used, set to Greenwich Mean Time GMT or Coordinated Universal Time (UTC) as it is now known. In other words Summer Time or Daylight Saving Time is always ignored.

Calculation of Time of Flight (Still Air)**The DST formula**

10. If a car travels 120 miles at 60 mph, it will take 2 hours to complete the journey. This is found by the Distance/Speed/Time (DST) formula:

$$TIME(T) = \frac{DISTANCE(D)}{SPEED(S)} = \frac{120}{60} = 2$$

$$SPEED = \frac{DISTANCE}{TIME} \quad DISTANCE = SPEED \times TIME$$

11. This same formula can be used for an aircraft flying in still air. For example, a Nimrod flying at a TAS of 400 kts over an 1800 nm sector will take 4 ½ hours in still air.

$$SPEED = \frac{DISTANCE}{TIME}$$

12. This formula can also be re-arranged to find distance or speed if the other two quantities are known.

13. Here is an example of how to calculate speed given distance and time. How fast must we go to cover 1500 nm in 5 hours?

Using:

$$SPEED = \frac{1500}{5} = 300kts$$

Manipulation of equations

Simple equations can easily be manipulated using cross multiplication. That is, numbers on one side of the equation can cross the equals sign to the other side provided that, if the number is below the line (division) when it changes side, it comes above the line multiplication) and vice-versa. For example:

$$DISTANCE = SPEED \times TIME \quad \longrightarrow \quad \frac{DISTANCE}{TIME} = SPEED$$

$$DISTANCE = SPEED \times TIME \quad \longrightarrow \quad \frac{DISTANCE}{SPEED} = TIME$$

Self Assessment Questions

1. One degree of latitude represents:

- a. 1 nm
- b. 6 nm
- c. 60 nm
- d. 360 nm

2. Glasgow is due north of Plymouth (approximately on the same meridian). If Glasgow is latitude $55^{\circ}50'$ and Plymouth is latitude $50^{\circ}25'$ what distance are the two places apart?

- a. 525 nm
- b. 275 nm
- c. 450 nm
- d. 325 nm

3. In the RAF, aircraft speeds are generally expressed in:

- a. metres per second
- b. miles per hour
- c. nautical miles per second
- d. knots

4. An ASI has an instrument correction factor of +3 kts and a pressure correction factor of -1 kts. If the instrument reads 130 kts what is the CAS?

- a. 130 kts
- b. 132 kts
- c. 133 kts
- d. 134 kts

5. A Tornado is flying at a TAS of 400 kts. How far will it travel in 2 hrs?

- a. 200 nm
- b. 200 km
- c. 800 nm
- d. 800 km

CHAPTER 2

THE TRIANGLE OF VELOCITIES

Introduction

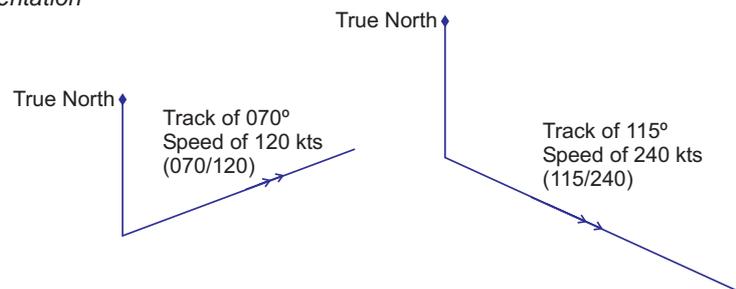
1. So far, we have talked about flying in still air conditions. It is now necessary to consider the wind, which is simply air that is moving.

Vectors and Velocity

2. Whenever we talk about aircraft or wind movement, we must always give both the direction and speed of the movement. Direction and speed together are called a velocity. A velocity can be represented on a piece of paper by a line called a vector. The bearing of the line (usually relative to true north) represents the direction of the movement, and the length of the line represents the speed.

Representing vectors

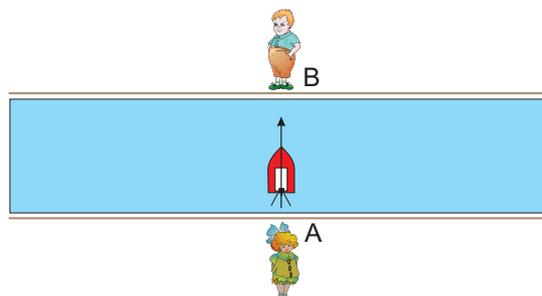
Fig 2-1 Representation of vectors



The Vector Triangle

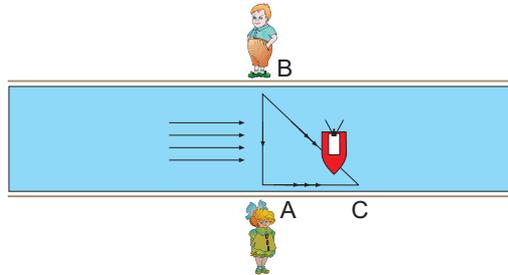
Vectors can be added together

3. Let us begin with a situation in everyday life, which we can easily relate to the vector triangle. Imagine two children, one either side of a river, with a toy boat driven by an electric motor (Fig 2-2). The boat has a rudder to keep it on a straight course and has a speed of 2 knots. Child A stands on the southern bank and points the boat at her friend on the other side of the river. If the river is not flowing the boat will cross the river at right angles and reach child B on the other side.



4. However, rivers flow downstream towards the sea, so let us look at a river where the speed of the current is 2 knots. Picture child B putting the boat in the water pointing at his friend. Where will the boat reach the other bank?

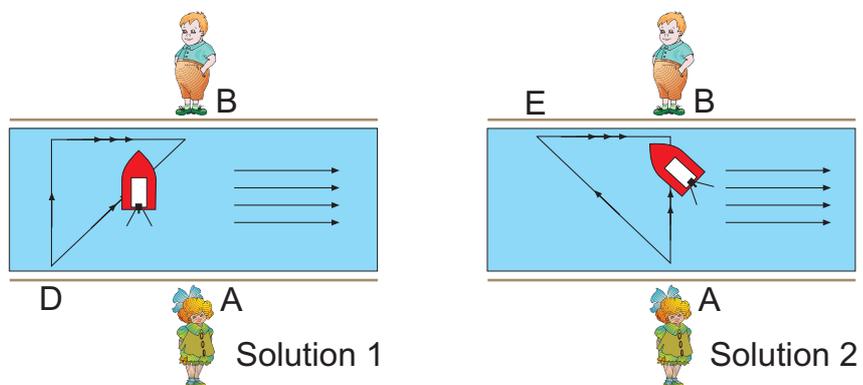
Fig 2-3 When the water in the river is moving



Vector Triangle

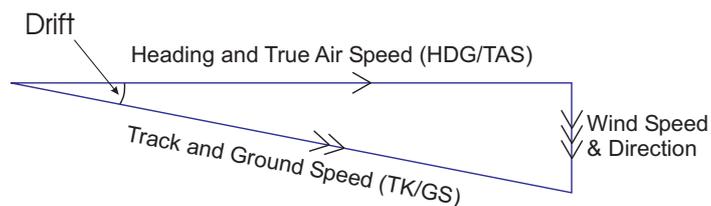
5. The vector triangle solves this problem for us. In Fig 2-3, the velocity of the boat is shown as the line with the single arrow crossing the river, and the water velocity is the line with the three arrowheads pointing downstream. The two lines are the same length as they both represent a speed of 2 knots. By joining the two ends to make a triangle, the third side of the vector triangle (called the resultant and indicated by arrowheads) represents the actual movement of the boat as it crabs across the river. By use of Pythagoras's theorem it can be shown that the speed of the boat over the riverbed is 2.83 knots. So, child A has to walk downstream to point C to collect the boat. If she now wishes to send the boat back to B, without making child B walk along the bank, she must walk upstream twice as far (to a point D – see Fig 2-4) before launching the boat again on a heading at right angles to the stream. Another solution is possible if child A can alter the speed of the boat, she can go to point A, set the speed to 2.83 knots and launch the boat pointing at E, because it will then travel directly from A to B as required.

Fig 2-4



The air Triangle of velocitiesThe Air Triangle

6. Exactly the same triangle can be used to show the motion of an aircraft through the air which is itself moving. There are two differences. The first is that we label the triangle with new names (eg wind instead of current).

Fig 2-5 Air triangle of velocities**Some definitions**

The second is that as the aircraft speed is normally a lot more than the wind speed, the triangle will be much longer and thinner than the squat triangle, which represents the movement of the toy boat. There are 6 components of the air triangle, and they are described in the next 3 paragraphs.

Heading and TAS

7. The heading of the aircraft is the direction that the aircraft is pointing (ie what is on the compass). The TAS is the speed of the aircraft through the air, taking into account all the corrections mentioned in Chapter 1. This vector, shown by a line of scale length, carries one arrow. Remember, the vector represents 2 components, HDG and TAS.

Wind Velocity

8. This is a scale line with 3 arrows; it represents 2 more components, the wind speed and the direction FROM WHICH IT IS BLOWING (northerly in the diagram).

Track and Groundspeed

9. The remaining 2 components in the air triangle are the direction and speed that the aircraft is actually moving over the ground. This vector has 2 arrows, and it is the resultant of the other 2 vectors. Note that the number of arrows put on each vector is simply a convention that is used, to avoid confusing one with the other.

Drift

10. Drift is the angle between the heading and track vectors and represents the angle at which the aircraft is being blown sideways. It is labelled Left or Right, depending on which way the aircraft is blown. Of course, if you fly directly into wind or directly downwind, heading will be the same as track and there will be no drift. The TAS and GS will in this case differ by exactly the value of the wind speed.

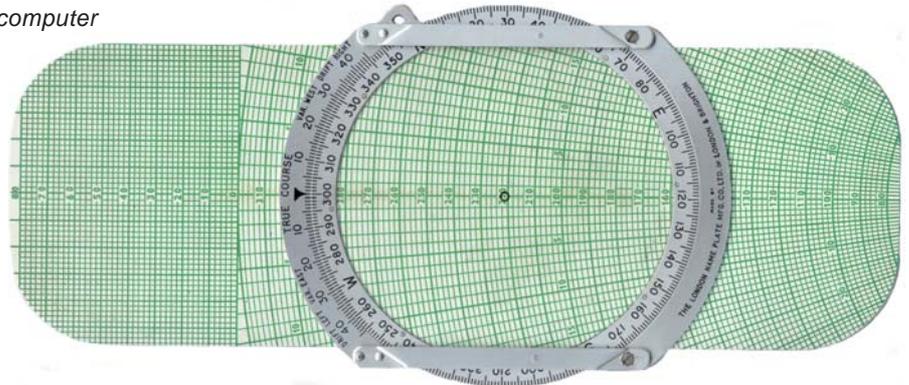
The Real World

11. All this theory is all very well but what happens in the real world? There are three likely scenarios when we have to solve the triangle of Velocities. The first is at the planning stage of a flight, once we have decided our route; we know our tracks and distances from start to destination. We also know the performance of the aircraft and given the temperature and height we can calculate the TAS, in addition to the temperature the Met Office will also provide us with the forecast W/V. Given 4 of the 6 elements of Triangle of Velocities (TAS, TK, Wind Speed and Direction) it is now possible to solve the other two quantities (GS & HDG) and then use the DST formula to calculate how long the flight will take. The second scenario is in the air when we know the TAS and HDG, and we can measure out TK and GS by watching our changing position over the ground. From these 4 items, we can calculate the W/V. The final scenario occurs when you know your heading and TAS and have a reliable W/V but are over a featureless area such as the sea and are unable to take any form of fix, then by applying the W/V to your heading and TAS you can calculate your track and Groundspeed. Once you have TK and G/S you can produce a deduced reckoning position (DR position) by applying the time from your last known position to the G/S to give you a distance along TK.

Computers

12. So far we have only talked about drawing vectors on paper. This is fine in the office or classroom but impossible in the cramped confines of a small aircraft. For many years, navigators have been using the Dalton hand held computer (Fig 2-6) and these are still used in the private flying world. The fast jet navigator in the RAF solves the triangle using a simplified mental calculation, which is beyond the scope of this course. In civil airliners an onboard electronic computer continually solves the triangle and many other things besides.

Fig 2-6 The RAF's Dalton computer



Magic Numbers

Magic numbers

13. All aviators, no matter how much help they have from electronics, have to do a lot of mental arithmetic. This can be made much easier if magic numbers are used. The numbers in question are the ground speeds in nautical miles per minutes; some examples are shown in the table below. It does not matter if you are flying in a Tutor or a Tornado, the method works equally well.

GS	nm/min	GS	nm/min
60	1	210	3 ¹ / ₂
80	1 ¹ / ₃	240	4
90	1 ¹ / ₂	300	5
100	1 ² / ₃	360	6
120	2	420	7
150	2 ¹ / ₂	480	8
180	3	540	9

Examples

14. You are in a Tornado at low level over Wales, doing 420 knots GS and you have 49 miles to run to the next turning point, how long will this take? Divide 49 by 7 and the answer is 7 minutes to go.

15. You are on a cross-country exercise in a Tutor, heading into wind at 80 knots GS. How long will a 20 mile leg take? To divide 20 by 1¹/₃, is the same as dividing by 4/3 or multiplying by 3/4. However, there is a much easier method in this example. As the distance is 1/4 of the speed, it must take one quarter of an hour.

6 minute magic

Six Minute Magic

16. With the slower speeds it is often easier to think in terms of how far do we go in 6 minutes (1 tenth of an hour). This is simply the ground speed with the last zero removed. So the Tutor above doing 80 knots, will travel 8 miles in 6 minutes. For short legs this is a much more useful calculation.

Time Of Arrival

ETA

17. A by-product of solving the triangle of velocities is that by making the DST calculation using GS and distance To Go, we can calculate the time that it will take to reach the next turning point or destination. This time is called Estimated Time of Arrival (ETA) and is important both for fuel calculations and for Air Traffic control purposes. A particular application of this is the ETA for the destination. If you do not arrive on time, Air Traffic will have to take overdue action; very similar to the way a search party goes out to find a group of walkers who have not returned from a mountain trek on time.

Conclusion

18. Hopefully this chapter will have convinced you that despite all the computers, some mental arithmetic is essential, whether you plan to join the RAF as aircrew, become an airline pilot, obtain a PPL, or simply make the most of the available air experience opportunities. The starting point is the 6 times table; no one in their right mind would dream of aviating without this knowledge.

Self Assessment Questions

1. What do the initials TAS stand for?
 - a. True Air Speed
 - b. Track Air Space
 - c. Track Aviation Speed
 - d. True Air Space

2. The 4 vectors shown represent the movement of 4 aircraft. Which aircraft is travelling due south?
 - a. W
 - b. X
 - c. Y
 - d. Z

3. In the diagram above which aircraft is travelling the fastest?
 - a. W
 - b. X
 - c. Y
 - d. Z

4. In an Air Triangle vector diagram the 3 vectors are:
 - a. Heading and TAS - Drift angle - Wind speed and direction
 - b. Track and ground speed - Wind speed and direction - Drift velocity
 - c. Wind speed and direction - Track and ground speed - Heading and TAS
 - d. Wind speed and direction - TAS and heading - Drift speed and direction

5. A Tutor when travelling at a GS of 90 kts will cover 11/2 nm in one minute. How long will it take to cover 30 nm?
 - a. 20 mins
 - b. 30 mins
 - c. 45 mins
 - d. 60 mins

CHAPTER 3

THE 1 IN 60 RULE

Introduction

1. In modern aircraft it is often necessary to do quick mental calculations to check that the navigational computer is still making sense and that we have not fallen into the garbage in, garbage out trap. The previous chapter looked at progress along track (DST and ETA); we now need to consider our position across track. First though, a couple of definitions.

Some definitions

Track Required

2. The track required is normally the line drawn on the map between the departure airfield and the destination, or from one turning point to another on the route.

Track Made Good

3. If for some reason the aircraft drifts off track and we can establish our position overhead some unique feature (a pinpoint), then the line joining the departure airfield and the pinpoint is known as the Track Made Good (TMG).

Revised Track

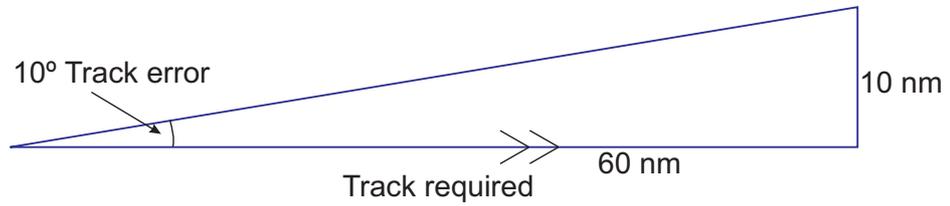
4. From a pinpoint, which is off the track required, we have 2 options. One would be to regain the required track, but more normally we would draw a line from the pinpoint to the next turning point. This is called the revised track.

The 1 in 60 rule

1 In 60 Rule

5. The 1 in 60 rule states that if an aircraft flies a TMG 1° in error from the required track, then after 60 miles of flying the aircraft will be one mile off the required track. This can be proved with trigonometry but all you need to know is how to use the triangle. The example in the diagram at Fig 3-1 shows that with a 10° track error, after 60 nm the aircraft would be 10 nm off track.

Fig 3-1 After 60 nm the error is 1 nm for every 1 off track



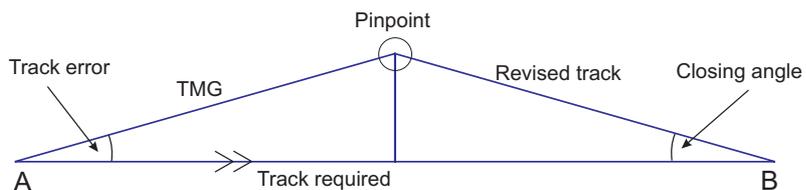
6. The 1 in 60 rule holds good for track errors up to 23° beyond that the difference in length of the two tracks (TMG and Track required) becomes too great and the approximation will not work.

Application Of 1 in 60 Rule

Pinpoint 1/2 way along track

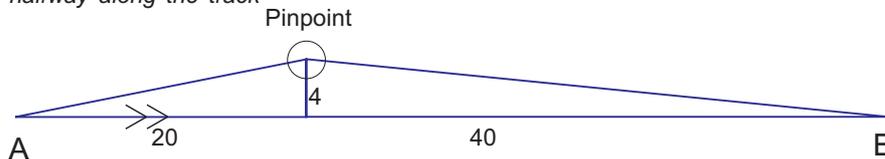
7. The simplest application of the 1 in 60 rule is when a pinpoint is taken exactly halfway along track. From the diagram below (Fig 3-2) you can see the triangle formed as the aircraft drifts off track is exactly mirrored by the triangle showing the aircraft regaining track.

Fig 3-2 A pinpoint is taken exactly halfway along the track



8. As the triangles are the same size and shape, it is only necessary to alter heading to the right by twice the track error to ensure that the aircraft reaches point B (assuming the wind remains constant). As the pinpoint is taken halfway along track, the actual distances do not affect the results, but in the next example the only pinpoint available is one third of the way along track so some sums are needed.

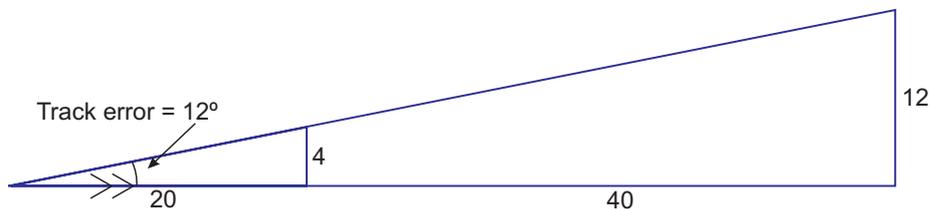
Fig 3-3 The pinpoint is less than halfway along the track



Find track error and closing angle

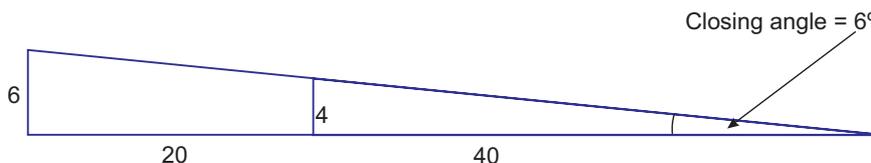
9. To solve this problem it is necessary to look at each triangle separately and use the 1 in 60 rule as applied to "similar triangles". Triangles are "similar" if they are identical in shape and differ only in size. Look at the left hand triangle and how this extends to make a 60 mile triangle. Simple multiplication then shows that if a 20 mile run produces a 4 mile error, a 60 mile run (3 times as far) will give a 12 mile error (3 times as large). Thus the track error angle is 12° .

Fig 3-4 The left hand triangle is extended to make the base 60 units long



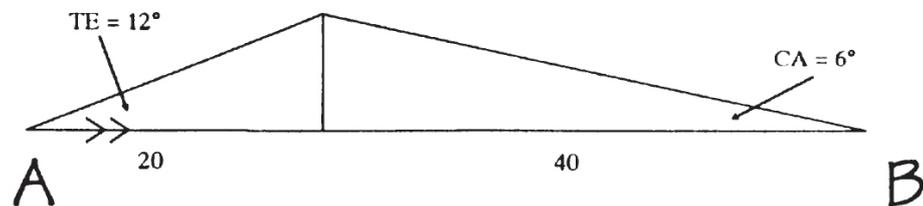
10. The second part of the leg is handled in the same way. Draw the right hand triangle from Fig 3-3 and extend the sides to make another triangle with a 60 nm base. A 4 mile error at 40 miles becomes a 6 mile error at 60 nm, so the closing angle is 6° .

Fig 3-5 The right hand triangle is extended in the same way



11. Once you understand the method and can do the mental arithmetic, you can then omit the drawing of the triangles in Figs 3-4 and 3-5. Putting these figures back into the original problem from Fig 3-3, you can see that the track error angle and the closing angle are added together to give 18, this is the amount that you need to turn right in order to regain track at point B.

Fig 3-6 Adding the TE and CA gives the amount of turn required



Practical Application

Keep it simple

12. The 1 in 60 rule is used a great deal in both military and civil flying. Because pinpoints are not always available when we want them, we are often left with awkward numbers that do not lend themselves to mental arithmetic. The solution is to use approximate numbers that are easily handled, either round numbers like 20, 30, 40 or those divisible by 6. Bear in mind that the answer is only needed to whole degrees so ultimate accuracy is unnecessary. Remember also, that once a pinpoint is found, it takes you a measurable time to do the calculations, during which time you are drifting further off track so if you have any rounding up to do, ensure that you turn more than the precise calculation rather than less.

Self Assessment Questions

1. If an aircraft flies for 60 nm with an error of 1° in its heading, it will be 1 nm from its intended track. This is understood as:

- a. The vector triangle rule
- b. The distance/time/velocity rule
- c. The 1 in 60 rule
- d. The revised track rule

2. If an aircraft flies for 60 nm with an error of 12° in its heading, how far will it be from its intended track?

- a. 1 nm
- b. 6 nm
- c. 12 nm
- d. 60 nm

3. An aircraft when flying from A to B is found to be off track at the pinpoint shown below. The pilot calculates the track error as 8° and the closing angle of 4° . By how much does the pilot need to turn to reach point B?

- a. 4°
- b. 12°
- c. 8°
- d. 16°

4. An aircraft flying from A to B finds that after 30 nm it is 4 nm off track. If it has a further 60 nm to travel by how much does the pilot need to turn to regain the intended track at B?

- a. 4°
- b. 8°
- c. 12°
- d. 14°

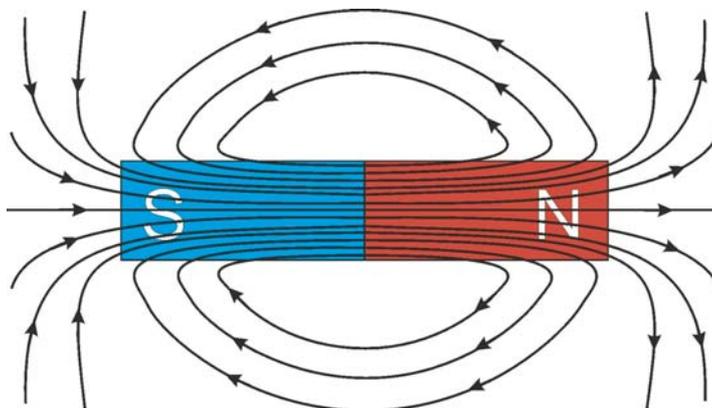
CHAPTER 4

COMPASSES

Introduction

1. Earlier in your Navigation training, you will have learned about the difference between True North and Magnetic North and how to use a simple hand held compass such as the Silva. To understand aircraft compasses, their strengths and weaknesses we need to look into the subject a little deeper. The first thing you need to understand is the shape of the magnetic field around a magnet. An experiment at school with a magnet and iron filings, will produce a pattern similar to that shown in Fig 4-1 below.

Fig 3-6 Magnetic Lines of force around the Earth

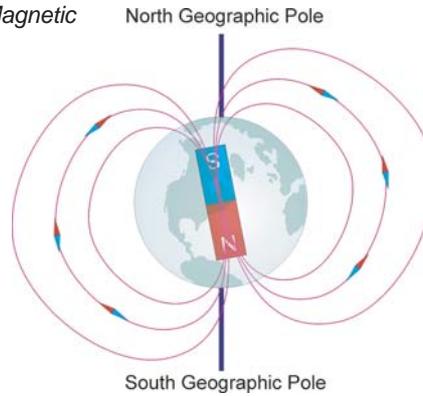


The Earth's Magnetic Field

2. The Earth's magnetic field, follows the same pattern as the field round a bar magnet but needs a little explaining. A diagram of the Earth's field is shown over the page as Fig 4-2. The red end of a magnet (known as the North Pole) is in fact a north-seeking pole. Therefore, as opposites attract it can be seen that if the red end of our compass needle is to point to the North Magnetic Pole, then in reality the North Magnetic Pole must, in magnetic terms be a south pole.

You will note when examining Fig 4-2 that the lines of force are only parallel to the surface of the Earth at the Equator. Indeed, at the poles the lines of force are vertical! A compass needle will try to follow the lines of force but is constrained by the construction to stay almost horizontal. The end result of this is that the more vertical the Earth's field, the weaker the directional force on the horizontal compass needle becomes. At our latitude, the lines of force point down at an angle (known as the angle of dip) of 65° ; once the angle exceeds 75° (which occurs about 1200 miles from the Poles) the directional force becomes so weak as to render magnetic compasses virtually useless.

Fig 4-2 The Earth's Magnetic Field



3. In an aircraft, the simplest form of compass is the Direct Indicating Compass (shown at Fig 4-3), which looks very similar to the car compass, which can be bought from accessory shops.

Fig 4-3 A Direct Indicating Compass



The Direct Indicating Compass

4. The Direct Indicating Compass (DIC), like the hand held Silva compass, has a magnet suspended in liquid, which helps to dampen any movement. However, it looks very different, having the appearance of a squash ball inside a very small goldfish bowl. The points of the compass are printed around the equator of the ball and the heading is shown against the index mark on the bowl. The magnet is hidden inside the ball.

DIC

Limitations of the DIC

5. The DIC has several serious limitations, so in most aircraft it is only used as a standby. These limitations are:
 - a. The suspended magnet will only give a correct reading in straight and level un-accelerated flight. During turns and when accelerating E – W, the magnet is swung to one side and thus gives false readings.
 - b. The DIC is located in the cockpit, and there it is affected by the magnetic fields emanating from both the metal the aircraft is made from and from the various electrical circuits in the aircraft. These other magnetic fields badly affect the accuracy of the DIC.
 - c. The driving power of the horizontal portion of the Earth's magnetic field is only strong enough to turn a compass needle; it does not have sufficient torque to drive repeaters at other crew positions in the aircraft.
 - d. The DIC only indicates magnetic heading, modern aircraft may require True or Grid headings.
 - e. At high magnetic latitudes (above 70° North or South) the DIC becomes sluggish and unreliable because the angle of dip is so steep and the directional force is so weak.

Advantages of the DIC

6. The DIC does however, have three advantages.
 - a. It is very simple and therefore reliable.
 - b. It is very cheap and lightweight.
 - c. It does not require any form of power and so will continue to work even after a total power failure in the aircraft.

Counting paces

The Gyro Magnetic Compass

7. To overcome the limitations of the DIC, the Gyro Magnetic Compass was invented. The components are as follows:
 - a. A Magnetic Detector Unit, which electrically senses the direction of Earth's magnetic field is normally situated in the wing tip.

- b. A Gyroscope, which continues to point to a fixed point in space, regardless of any manoeuvres the aircraft may make.
- c. An Error Detector that senses any difference between the gyro and magnetic headings and applies a correction to the gyro at a pre-set rate.
- d. A controller or computer that applies corrections to the gyro to correct for the rotation of the Earth and the aircrafts flight path around the Earth.
- e. A display or displays to show the aircraft heading at required positions in the aircraft.
- f. Various amplifiers and motors to control the system and in some GMCs a roll cut out switch to minimise the effect of a turn on the Magnetic Detector Unit.

8. The basic principle of the GMC is that it uses the long-term accuracy of the detector unit combined with the short-term accuracy of the gyro. What this means is that the gyro, which is connected to the compass, is constantly corrected by the magnetic detector, which is correct during straight and level flight (and is more accurate than the DIC because being situated in the wing it is less affected by the deviating forces from other extraneous magnetic fields in the aircraft). During a turn, the gyro (which is unaffected by turns) is more accurate. If a roll cut out switch is used no error is fed from the magnetic detector to the gyro in the turn, if a roll cut out is not present, the error correction rate is low enough to only make a small effect which is removed when the wings are levelled.

9. A gyro magnetic system has considerably more torque than a DIC and can therefore provide outputs to repeater units in other positions in an aircraft and/or computers in the aircraft. The output to these repeaters can be easily modified so that they can display either true or magnetic heading.

Gyro Errors

10. A gyro suffers from both Real and Apparent errors. Real errors are caused by inaccuracies during the manufacturing process, however modern compass gyros will seldom have errors in excess of 1°/hour. Apparent errors, called as such because the gyro appears to be in error, are caused because we fly around a rotating Earth. Imagine aligning a gyro so that it points at the rising sun, ignoring any real errors, the gyro will continue to point at the sun until it sets in the evening. Now to an observer on Earth, the gyro will appear to have slowly changed direction from East through South to West, yet someone watching from space will have seen that the gyro continued

to point in the same direction and it was in fact the Earth that rotated. Apparent errors caused by the Earth's rotation or by us flying around the Earth follow simple mathematical formulae and are easily corrected, in many cases they are compensated for automatically using a corrector unit built into the compass system.

Inertial Navigation, GPS and Beyond

11. The fundamental problem with any system that relies on Magnetic North to provide direction is that if we require a True North direction then we must apply variation. This may seem simple enough but our knowledge of variation is seldom better than one degree. A modern aircraft with a heading error of one degree can easily have position errors in the order of 6 miles/hour, which nowadays is not acceptable. The Inertial Navigation System (INS) eliminates this problem and can align itself with True North without the need for variation. A typical inertial navigation system can achieve positional accuracies of one miles/hour. Whilst this accuracy may appear good, it is still a long way short of the latest development in navigation technology. Using Ring Laser Gyros or Fibre Optical Gyros to feed an Inertial Reference System, which is paired with a Global Positioning System (GPS), can produce a position, which is accurate to within 5 metres. The ultimate aim is to achieve millimetric accuracy, we are not there yet, but it will happen.

Self Assessment Questions

1. The initials DIC stand for:
 - a. Dual Identification Compass.
 - b. Direct Identification Compass.
 - c. Direct Indicating Compass.
 - d. Dual Indicating Compass.

2. Having a simple magnetic compass in the cockpit of an aircraft has both advantages and disadvantages. One such advantage may be:
 - a. Reads only magnetic headings.
 - b. Simple in operation but reliable.
 - c. May be affected by other instruments close by.
 - d. Swings about during aircraft manoeuvres.

3. The flux valve of a GMC is situated:
 - a. In the wing tip.
 - b. In the cockpit.
 - c. Inside the compass housing.
 - d. On the outside of the fuselage.

4. An Inertial Navigation System (INS) works by:
 - a. Frequent checks on position from satellites.
 - b. Using computers to keep a record of the aircraft's movement from a known starting point.
 - c. Using computers to continually work out the error in the magnetic readings and compensate accordingly.
 - d. Frequent checks on position using ground based radar stations.

CHAPTER 5

WEATHER

Introduction

1. You will have previously studied the weather as it relates to walking in the hills. It is the same weather that affects aircraft operations but with one major difference; icing is a far more serious problem for an aircraft than it is for a walker.

Meteorological Conditions

2. Simple aircraft such as basic trainers are not equipped with instruments to enable them to safely fly in cloud or fog, nor do their student pilots have sufficient experience. Consequently, it is necessary to define the weather conditions in which beginners may fly. These are called Visual Met Conditions (VMC) and a simplified version of the rules are set out in the table below.

Above 300'	Below 3000'
Visibility - 8km or better Distance from cloud: 1000' vertically 1500m horizontally	Visibility - 5km or better Distance from cloud: 1000e' vertically 1500m horizontally
NB Aircraft flying below 140 kts and in sight of the ground may use 2 km visibility and merely have to keep clear of the cloud.	

3. It follows that if an aircraft flies in weather worse than shown in the table, it must have the necessary instruments to fly in or near to cloud or in poor visibility. This weather is known as Instrument Met Conditions (IMC). Only aircraft with suitable equipment and pilots with suitable instrument ratings may fly in IMC.

The Visual Circuit

4. In the early stages of flying, a trainee pilot will not want to lose sight of the runway when flying circuits in order to practice take-offs and landings. To achieve this, VMC is needed and normally the aerodrome controller will decide if the weather

is good enough. If the circuit height is 1000' then the lowest cloudbase will need to be above this (usually 1500') and the visibility will need to be good enough to be able to see the runway from anywhere in the circuit (usually 5 km).

Take off into Wind

Surface Wind

5. In earlier chapters on navigation you will have learned how we deal with wind and drift when transiting from A to B. At the aerodrome we still have to take account of drift but the surface wind is of greater concern. If the conditions are not completely calm, we need to take note of the wind direction and arrange to take-off and land as closely as possible, directly into wind. This is because the airspeed of the aircraft determines when it can safely lift off the runway. In strong winds this can make a big difference to the time and distance it takes to get airborne. Into a strong wind an aircraft reaches flying speed very quickly and can therefore use a shorter runway. If we make the mistake of trying to take-off downwind we could well reach the end of the runway before reaching flying speed and this could be disastrous.

Wind Component

Headwinds and crosswinds

6. It is very rare to find the wind blowing exactly along the runway, even though runway directions are chosen to take account of the prevailing wind. Normally the wind will blow partly across the runway and we need to be able to calculate how much crosswind and how much headwind there is. This can be done by drawing vectors (see below) but it is more normal to consult a table (Fig 5-2) or alternatively use a simple mental method which gives approximately the right answer (Fig 5-3).

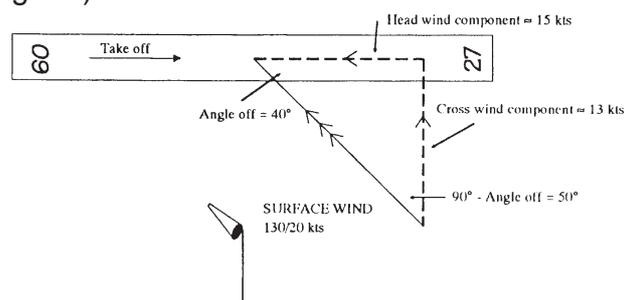


Fig 5-2 Table showing headwind and crosswind components

		Angle between wind direction and runway heading for crosswind component.								
		10°	20°	30°	40°	50°	60°	70°	80°	90°
Wind Speed in Knots	5	1	2	2	3	4	4	4	5	5
	10	2	3	5	6	7	8	9	9	10
	15	3	5	7	9	11	13	14	14	15
	20	3	7	10	13	15	17	18	19	20
	25	4	8	12	16	19	22	23	24	25
	30	5	10	15	19	23	26	28	29	30
Note: These angles are from the vector triangle shown in Fig 5-1 ie 90° minus angle off.		80°	70°	60°	50°	40°	30°	20°	10°	0°
		For headwind component - Angle between wind direction and runway heading.								

How to use the table

From Fig 5-1 the angle between the runway heading and the wind direction = 40° (angle off). To obtain the crosswind component use the top row of angles and find the 40° column - follow it down until you meet the correct windspeed row, in this case 20 kts. This gives the cross wind component as 13 kts. For the headwind use the angles at the bottom of the table.

Angle between wind direction and runway heading for crosswind component	
0° - 15°	Zero
15° - 30°	1/4 of wind strength
30° - 45°	1/2 of wind strength
45° - 60°	3/4 of wind strength
60° & above	Full wind strength

Fig 5-3 The quick approximate method

Shallow Fog

7. As fog starts to form in the early evening, there is often a very shallow layer, maybe only a few feet thick, close to the ground. For a pilot in the circuit, looking down into the layer, this is virtually invisible. This is particularly true at night, when the runway lights show clearly when directly above them. However, as the aircraft joins the glide slope approaching the runway, the pilot will be looking through the fog at a shallow angle. The fog will suddenly appear to be much thicker and may well prevent the aircraft from landing as the runway and/or the lights are no longer visible. This slant visibility can be measured and is known as Runway Visual Range (RVR). If the RVR is less than about 800 metres a safe landing will be difficult or impossible.

Precipitation

8. Precipitation is a fancy word which covers rain, sleet, snow, hail and anything else wet or frozen which falls from a cloud (no, not fish!). For an aircraft on the ground, rain will not be a problem so long as the aircraft does not leak. If the rain is heavy enough it might restrict visibility or flood the runway. However, if the precipitation is frozen or the temperature at ground level is below zero, the precipitation will stick to the airframe and cause serious problems during the take-off. Loose snow can be brushed off an airframe but once it is stuck to the surface it has to be treated with de-icing fluid. This is not always successful so the decision as to whether to take-off in these conditions can be critical.

Airborne Hazards

9. Apart from thunderstorms, which are dealt with in the next ACP, icing is still the major problem with the weather once in the air. Even in VMC, icing can form on an airframe at certain temperatures, especially when flying a cold aircraft through rain which is only just above freezing point.

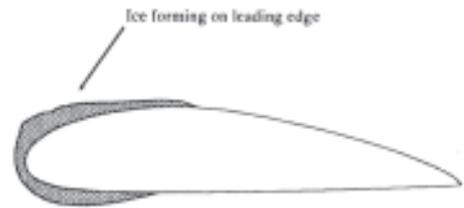
Icing

10. Why should icing be such a problem? In a car the main problem on a frosty morning is the frozen windscreen. In an aircraft this is easily cured by heating the windscreen. But you cannot heat the whole of the airframe and so, as ice sticks to

the surface, the shape of the surface changes and eventually the wings cease to look like an aerofoil and no longer generate enough lift to keep the aircraft airborne.

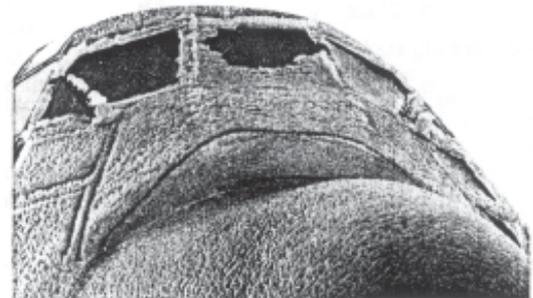
11. Not only does the shape of the wing change but as ice sticks to the airframe, the weight increases. Normally, lift and weight should be equal but in icing conditions, weight is increasing at a time when the lift is decreasing.

Fig 5-4 The Wing shape changes as ice builds up



The net result of this effect is that the aircraft flies like a brick. Icing can also affect other aspects of the operation of the aircraft as it forms on the undercarriage, control surfaces, radio aerials and so on. Of greater importance though, is the effect on engine performance. Both jet and piston engines are affected and the best advice is simply to keep away from icing, especially with small aircraft which have little or no ice protection.

Fig 5-5 Severe icing - photo courtesy of the aircraft's captain, Flt Lt Ray Evans



12. This picture of a Hercules was taken after an approach to a Canadian airfield through very severe icing. By the time the photographer reached the aircraft a lot of the ice had melted!

Conclusion

13. The weather is a very important subject to aviators. Even on a seemingly nice day you still need to be aware of the problems that can occur. Weather can be very unforgiving and can seriously affect the operation of the aircraft when it is not your day.

Self Assessment Questions

1. What do the initials VMC stand for?
 - a. Visual Meteorological Conditions
 - b. Verbal Meteorological Conditions
 - c. Visual Metric Conditions
 - d. Verbal Metric Conditions

2. An aircraft should always take off into wind to:
 - a. Increase the length of take off run
 - b. Decrease the length of take off run
 - c. Increase ground speed at take off
 - d. Reduce air speed at take off

3. While attempting to land on runway 09 (heading of 90°) a pilot is informed of a surface wind blowing at 25 kts on a heading of 140°. Using the table in Fig 5-2 find the strength of the cross wind.
 - a. 16 kts
 - b. 19 kts
 - c. 22 kts
 - d. 23 kts

4. Why is icing such a problem for aircraft?
 - a. De-icing is expensive and time consuming
 - b. The aerofoil shape of wings is spoiled - decreasing lift
 - c. The aircraft has to fly slower due to poor visibility
 - d. More power is required to keep the inside of the aircraft warm

4. Rain, sleet, snow and hail are collectively known as:
 - a. Participation
 - b. IMC
 - c. Precipitation
 - d. VMC

CHAPTER 1



INSTRUCTOR'S GUIDE

AIR NAVIGATION

Page 32.3.1-1 Para 2

DISTANCE

1. Distance on the Earth's surface may be expressed in one of the following three units:

The Nautical Mile

The Statute Mile, and

The Kilometre.

2. To achieve standardisation of units, the Systeme International d'Unités, abbreviated to SI Units, introduced the metre as the basic unit of length. At first sight, this implies that the kilometre should take the place of the nautical mile. However, this was not accepted as a rational proposal, mainly due to the fact that the kilometre is not related to the sexagesimal system of measurement of angles (a system based on the number 60), and since navigation is greatly concerned with angular measurement, the impracticalities of the proposal led to the retention of the nautical mile. It is appropriate therefore to clearly define all three units.

NAUTICAL MILE

3. A nautical mile is the length of arc of a great circle subtended by an angle of one minute at the centre of the Earth.
4. In effect, this means that an arc of the surface of the Earth which is subtended by an angle of one degree at the Earth's centre, contains 60 nautical miles. Such a unit of distance for navigational purposes has an obvious advantage over a unit of length such as the land mile. It means, for example, that the distance between the Equator and either pole will be $90^\circ \times 60$ nautical miles, since the angular distance is 90° and there are 60 minutes within each degree. Similarly the distance around the Equator will be $360^\circ \times 60$, or 21,600 nautical miles.

STATUTE MILE

5. The statute mile, or land mile, was derived from the Roman mile, a unit of 1000 Roman paces, the word coming from the Latin mille, meaning thousand. This mile was an arbitrary measure, and not related to the size of the Earth.
6. The statute mile is a unit of 5280 ft, the foot being one third of the arbitrary unit of length known as the yard.

KILOMETRE

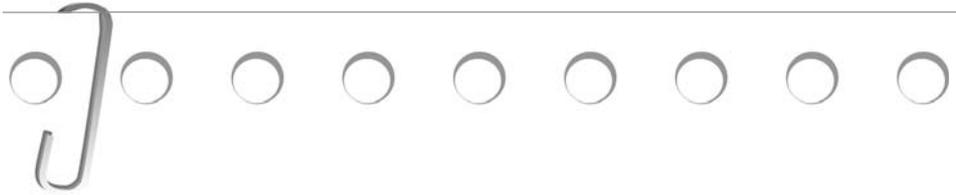
7. A kilometre is 1/10,000 part of the distance between the equator and either pole. This unit has the merit that it is related to the size of the Earth, and would appear to be a useful one in navigation. It is not, however, related to the angular measurement of 60 minutes per degree, or 90 degrees to the right angle, and is not ideally suited to replace the nautical mile although it is gradually replacing the statute mile. A kilometre is accepted to be equivalent to 3280 ft. There are 1000 metres in 1 kilometre.

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SPEED

8. Speed is a rate of change of distance, and since there are three units of distance there are also three units of speed. They are (i) the Knot, which refers to nautical miles per hour, (ii) mph, which refers to statute miles per hour, and (iii) kph, which refers to kilometres per hour.

CHAPTER 1



Aircraft speed is normally measured in the maritime tradition using the knot, although at speeds approaching, or beyond, the speed of sound another important units needs to be added. This unit is the "Mach" number.

9. The mach number relates the aircraft's speed to the local speed of sound. It may be more precisely defined as the ratio of the speed of the aircraft through the air, to the speed of sound in the aircraft's vicinity.

This is shown in the following formula:

$$\text{Mach Number} = \frac{\text{True Air Speed}}{\text{Speed of Sound}}$$

10. Simply, if an aircraft is flying at half the speed of sound, then it will have a mach number of 0.5.

11. The speed of sound varies according to the temperature surrounding the aircraft. At high level, where temperature is low, the speed of sound is less than at sea level, so that the mach meter is designed to take care of two variables - the variation of aircraft speed, and the variation of the speed of sound.

$$1^\circ = 60 \text{ nm}$$

therefore

$$10^\circ \times 60 = 600 \text{ nm}$$

$$1' = 1 \text{ nm}$$

$$\text{so} \quad \quad \quad 55' = 55 \text{ nm}$$

$$\text{TOTAL} \quad \quad \quad = 655 \text{ nm}$$

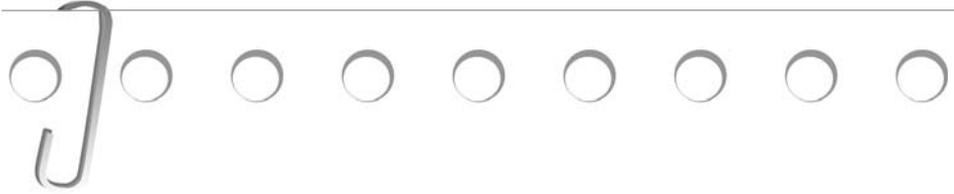
AERONAUTICAL CHARTS

A map, or chart, is primarily intended to portray sections of the Earth's surface on a flat sheet of paper. The manner in which meridians and parallels are drawn, and the information overprinted on the surface depends on the purpose of the map. An atlas for example may need to portray large areas with the locality of certain features clearly indicated. Its purpose is usually to give geographical information, and to do this, the cartographer may show parallels and meridians as straight parallel lines which lie at right angles to one another, or, he may show meridians as converging straight lines and parallels as arcs of concentric circles centred on the nearer pole. If the atlas fails to accurately represent angles correctly over the whole area, then, quite apart from the small scale being used, it would not form a suitable projection of the Earth's surface to be useful for navigational purposes. The requirements of navigational charts vary however according to their particular application.

It is important now to distinguish clearly between the words "projection", "chart", and "map", since these words are frequently used in this chapter and elsewhere.

A projection is an arrangement on a flat sheet of paper, of a graticule of meridians and parallels which are assumed to be on the Earth's surface. All maps and charts are therefore projections of one sort or another.

CHAPTER 1



A chart is a projection which carries very little topographical detail and which is mainly used for navigational plotting.

A map is a projection over which are printed details of topography, culture and other geographical information.

THE KNOT

The unit of measurement of a vessel's speed, corresponding to one nautical mile per hour. The knot originated from sailing ships who measured their speed by attaching a float to the end of a rope which had knots tied every 7 fathoms (12.8m) along its length. The float was then lowered into the water and the number of knots paid out in 30 seconds was the speed of the ship.

CHAPTER 2



INSTRUCTOR'S GUIDE

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Today, the modern air navigator is assisted in his work by a large back up of instrumentation and equipment which provide information of height, speed, direction, distance flown, distance to fly, track guidance and position. Frequently, automation is used to control both the flight path and the landing procedure, and the idea of total automation from take off to landing by computer/data transmission to an aircraft's automatic pilot is perfectly feasible. All these systems, however sophisticated, are nonetheless aids to navigation and as such may not always be available. It is therefore bad philosophy to be totally reliant on the technology involved. Indeed there are many areas in the world where ground based electronic systems are not available, and there are also many aircraft which for one reason or another do not have these aids fitted. The air navigator must be able to cope adequately with any circumstance.

Page 32.3.2-1 Para 3BEARING

The direction of one point from another is termed a "bearing". Bearings may be measured from true north, magnetic north, or compass north but are normally plotted on a chart from true north.

Sometimes the direction of a point from the aircraft is measured in relation to the forward axis of the aircraft. In this case the bearing is called a "relative bearing". Relative bearings are measured clockwise from the forward axis of the aircraft through 360° and are frequently labelled with the letter (R). Thus, an object which is in line with the starboard wing of the aircraft has a relative bearing of 090(R). Similarly an object which is in line with the port wing has a relative bearing of 270(R).

When the relative bearing is known, the true bearing of an object from the aircraft can be calculated and depends upon the heading of the aircraft.

The triangle of velocities

1. A velocity is a rate of change of position in a given direction, and as such it is made up of both speed and direction. It is not correct to say that the velocity of an object is 30 knots; the speed may be 30 knots, but the velocity must also include a statement of the direction in which the object is moving.
2. A vector then must represent both speed and direction graphically, and is obtained by drawing a straight line whose length is proportional to speed using a constant scale, and whose direction is determined by reference to a datum line. In air navigation the datum line is normally true north, so that in the diagram, each of the three vectors described is illustrated against the direction of true north which is assumed to run towards the top of the paper.
3. You will need protractors for these exercises.

Example 1.

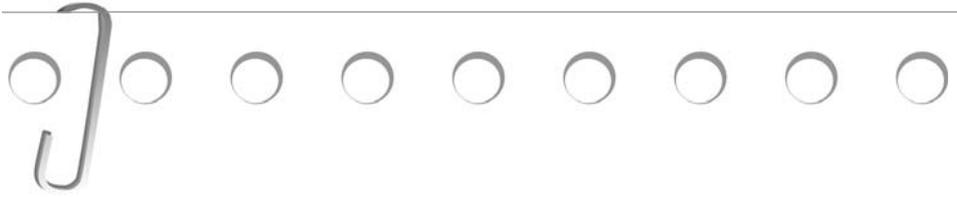
An aircraft heading 090(T) at TAS 200 knots, is making good a track of 096(T) at a ground speed of 220 knots. Determine the wind velocity.

Solution:

Draw a line from O in a direction of 090(T) to represent the aircraft heading. Mark this line with one arrow.

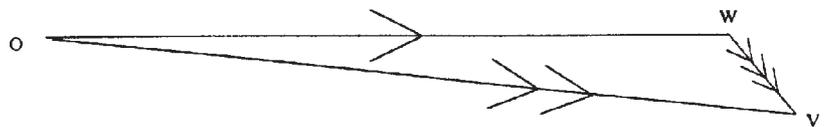
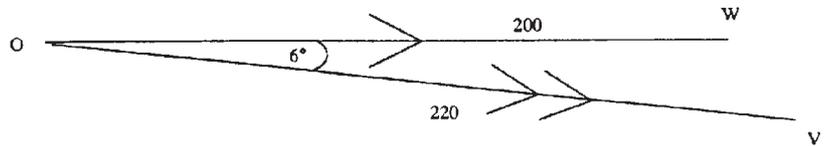
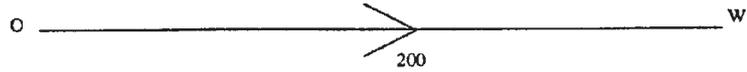
Using a constant scale make the length of the heading line, O to W, proportional to 200 knots

CHAPTER 2



From O draw in the track in a direction of 096(T), and make the line, length O to V, proportional to 220 knots. Mark this line with two arrows.

Join W to V, and measure its direction. The wind is blowing from W to V. Measure the length of the line for wind speed.



Answer: Wind Velocity = 320/30.

Example 2

An aircraft is heading 240(T) at an air speed of 250 knots. If the wind velocity is 140/50, determine the track made good and ground speed.

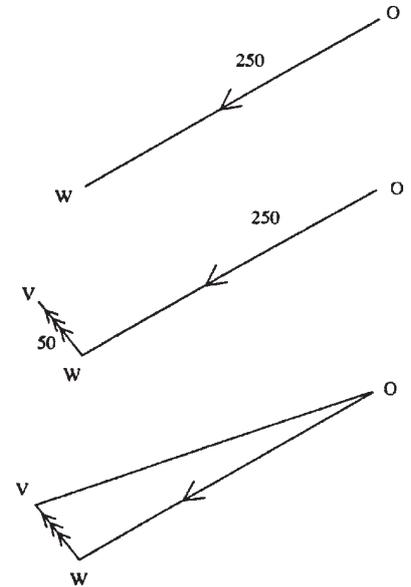
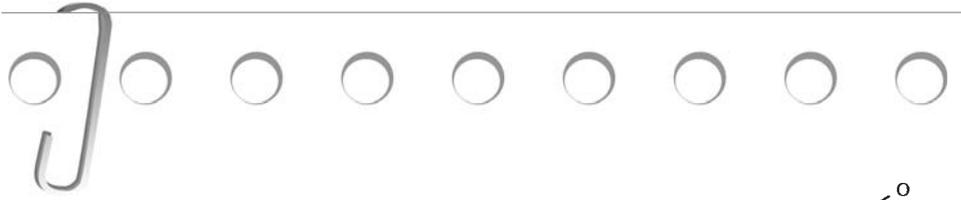
Solution:

Draw a line from O in a direction 240(T) and of length proportional to 250 knots. Mark the point W at the end of the line. Mark this line with one arrow.

From W draw a line in a direction of 320(T) to the point V which is at a distance corresponding to 50 knots of the speed scale given. This is the wind velocity and should be marked with three arrows from W to V. Notice the direction of the line is found from 140

Join O to V. Measure the direction from O to V to give the track made good. Mark the line with two arrows. Measure the length of the line to find the ground speed.

CHAPTER 2



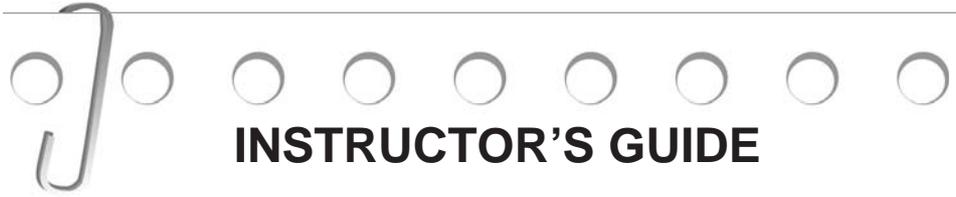
Page 32.3.2-6 Para 18

Answer : Track made good is 251 (T) and ground speed 264 knots.

The navigation computer

In the previous chapters the graphical construction of the triangle of velocities was described in order to solve some of the fundamental problems presented in air navigation. In practice however, a navigator should avoid wherever possible carrying out time wasting calculations, and in order to do this he is helped by a purpose-built mechanical aid known as a Navigation Computer. The navigation computer is virtually standardized in design, and is used to solve more than simply the triangle of velocities. On the reverse of the computer there is a circular slide rule capable of solving general arithmetical problems, and in particular those which are directly concerned with the general business of navigation. There are a variety of different navigation computers on the market, but they all fall fundamentally into the same physical appearance with minor modifications or additions to suit particular aircraft requirements.

CHAPTER 3



INSTRUCTOR'S GUIDE

Page 32.3.3-1 Para 5In-Flight Heading Corrections - 1-in-60 Rule

However accurately the heading may have been calculated and however carefully the pilot may steer the aircraft a wind velocity can often prove different to that forecast. Also, winds can change over quite short distances, particularly while flying from coastal regions to a position inland or vice versa.

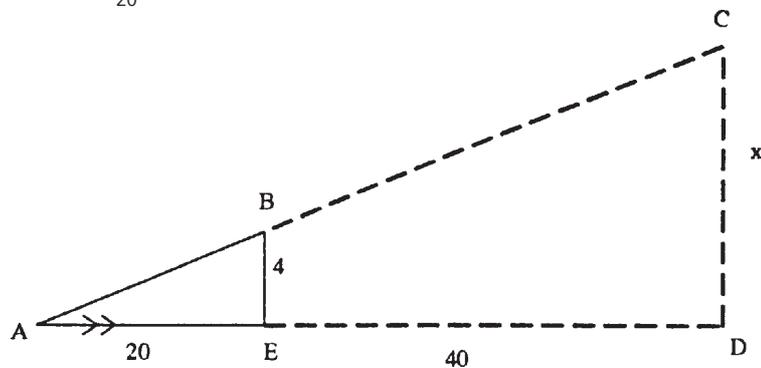
The ability to estimate the number of degrees off track (ie Track Error) and then determine what change of heading must be made (a) to fly the aircraft back on track, or (b) to reach the destination from the present, off-track position, is of obvious value to the pilot. Technique adopted is a simple one known as the 1-in-60 rule.

Where cadets find difficulty with simple proportions ie converting the velocity triangle into a triangle with one side = 60 - try this:

The triangles ABE and ACD are similar so:

$$\frac{4}{20} = \frac{x}{60}$$

$$\text{therefore, } x = \frac{4}{20} \times 60$$

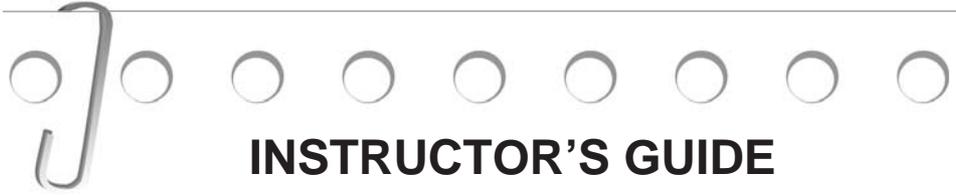


Since the 1 in 60 rule states that after 60 nm x = track error in degrees

$$\text{Track Error in degrees} = \frac{\text{Distance off track}}{\text{Distance Travelled}} \times 60$$

Similarly:

$$\text{Closing angle} = \frac{\text{Distance off track}}{\text{Distance remaining}} \times 60$$



Gyroscope

1. The term gyroscope is commonly applied to spherical, wheel-shaped bodies that are universally mounted to be free to rotate in any direction. One fundamental property they exhibit is gyroscopic inertia or rigidity in space which means that a spinning wheel of a gyroscope, tends to continue to rotate in the same plane about the same axis in space, even though its supporting frame may move.

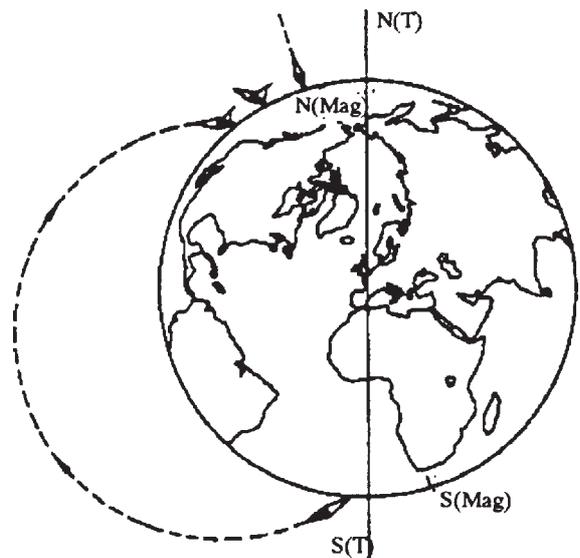
2. An example of this is the rifle bullet that, because it spins in flight, exhibits gyroscopic inertia, tending to maintain a straighter line of flight than it would if not rotating. Rigidity in space can best be demonstrated, however, by a model gyroscope consisting of a flywheel supported in rings in such a way that the axle of the flywheel can assume any angle in space. When the flywheel is spinning, the model can be moved about, tipped, or turned in any direction, but the flywheel will maintain its original plane of rotation.

3. Gyroscopes constitute an important part of automatic-navigation or inertial-guidance systems in aircraft, guided missiles, rockets, ships and submarines. In these systems, inertial guidance equipment comprises of gyroscopes and accelerometers that continuously calculate exact speed and direction of the craft in motion. These signals are fed into a computer, which records and compensates for course aberrations.

4. More advanced systems obtain guidance from laser gyros, which are not really inertial devices but instead measure changes in counterrotating beams of laser light caused by changes in craft direction.

Magnetic Limitations

As a compass needle approaches the magnetic poles of the earth the angle of dip increases to such an extent that it makes the instrument unusable. The angle of Dip is about 70° to the horizontal in England and 90° when at magnetic north.



Self Assessment Questions - Answer Sheet

Chapter 1 Page 32.3.1-6

Page 32.2.2-5 Para 15

1. c
2. d
3. d
4. b
5. c

Chapter 2 Page 32.3.2-7

Page 32.2.2-7 Para 17

1. a
2. c
3. b
4. c
5. a

Chapter 3 Page 32.3.3-5

1. c
2. c
3. b
4. c

Self Assessment Questions - Answer Sheet cont...

Chapter 4 Page 32.3.4-6

1. c
2. b
3. a
4. b

Chapter 5 Page 32.3.5-6

1. a
2. b
3. b
4. b
5. c