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DOCUMENT TITLE

NAVIGATION 1

CHAPTER 5 – VELOCITY TRIANGLE

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CONTENTS

VELOCITY TRIANGLE

5.1 Navigation Terminology

5.1.1 Wind

Wind simply means air in natural motion. Wind direction refers to the direction from which it originates. Wind is always expressed as a three-figure group and normally in degrees true.

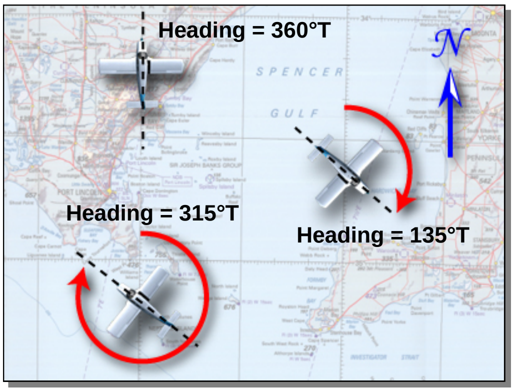
When wind direction is expressed in degrees magnetic, the letter 'M' is used to indicate the magnetic direction, e.g. 090M/35 (the wind is from 090°M at 35 knots).

Wind speed can be defined as the rate at which an air mass is moving, normally measured in knots. Wind velocity (W/V) is expressed as a five figure group, e.g. 090/20 (the wind is from 090°T at 20 knots), or as a six figure group when the wind speed exceeds 100 kts, e.g. 090/105 (the wind is from 090°T at 105 knots).

When the wind direction is in degrees magnetic it is written in a similar way, except the letter 'M' is utilised to indicate the magnetic direction, e.g. 090M/35 (the wind is from 090°M at 35 knots).

5.1.2 Heading

The term heading (HDG) refers to the direction in which an aircraft's nose is pointing. It is the angle measured clockwise <u>from</u> north <u>to</u> the fore and aft axis of the aircraft and may be expressed in degrees true, magnetic or compass.

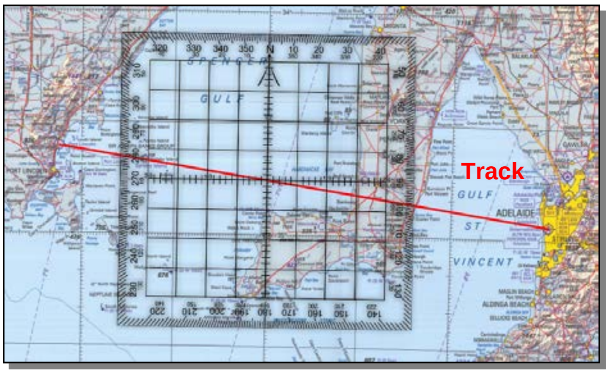


5.1.3 Track

Track (TR) refers to the direction of the path an aircraft is flying over the ground. The track the aircraft should follow, i.e. the one the pilot planned to follow, is known as the required track or flight planned track (FPT).

Track is normally measured in degrees true and can also be expressed in degrees magnetic when variation is applied.

FPT is determined by joining two places on a map and measuring the track direction with a protractor, clockwise from true north, as described in Chapter 4.



5.1.4 Track Made Good

The track the aircraft is actually following during a flight is known as the track made good (TMG).

Track made good (TMG) could differ from flight planned track (FPT) for the following reasons:

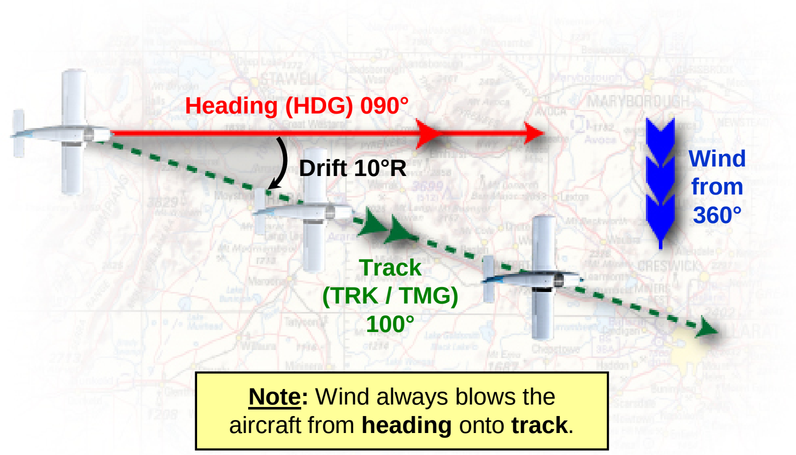
- The pilot has not flown an accurate heading exactly as planned.
- The actual wind velocity is different to the forecast wind velocity.
- Errors were made during planning when the heading to steer was calculated.

5.1.5 Drift

Drift is the angle between the aircraft heading and the aircraft track, and is the result of wind effect. Drift is expressed in degrees left (port) or right (starboard) of the aircraft heading. (Refer to the diagram below)

There are two cases to consider:

- Drift calculated at the flight planning stage, which is the angular difference between the planned heading and flight plan track.
- Drift that is actually occurring in flight, which is the angular difference between the current heading and track made good (TMG).

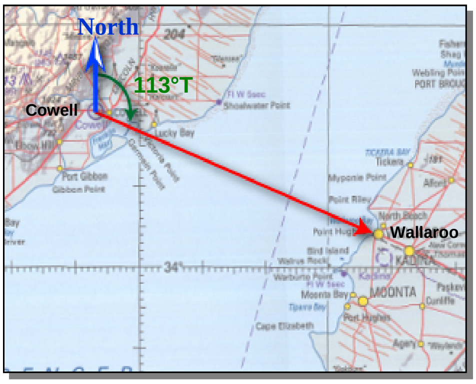


5.1.6 Bearing

The term **bearing (BRG)** refers to the direction of a given point on a map to another point, measured clockwise through 360° in degrees from north (true or magnetic).

Bearings can be either TO or FROM a certain point.

When a bearing is classified as TO, it is measured from the aircraft towards a reference external to the aircraft. For example the aircraft is overhead Cowell aerodrome and the true bearing TO Wallaroo is measured as 113°T.



In the example the bearing of 113°T TO Wallaroo represents the track the aircraft is required to make good to overfly the town.

Bearings are independent of heading. Even though the aircraft is changing heading the bearing TO Wallaroo would not be changing, if the aircraft's position change the bearing would also change.

When a bearing is classified as FROM it is usually measured at a reference external to the aircraft towards the aircraft. Bearings FROM external references are used to establish the position of the aircraft.

TO and FROM bearings are opposites, also referred to as reciprocals. To convert a bearing from TO into FROM (or FROM into TO) apply 180°:

- Add 180° when the original bearing is 179° or less.
- Subtract 180° when the original bearing is 180° or more.

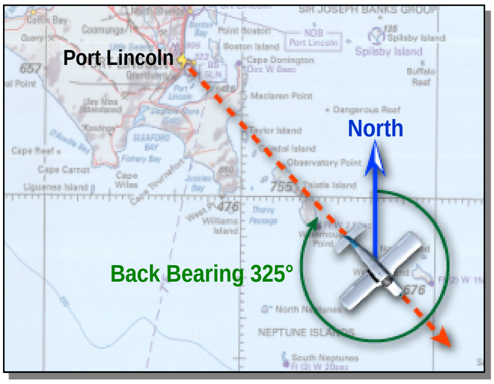
In the example the true bearing TO Wallaroo was 113°T. By adding 180° the true bearing FROM Wallaroo would be 293°T.

True bearings are converted into magnetic bearings using variation.

Example the true bearing FROM Wallaroo was calculated as 293°T. If the variation at Wallaroo is 7°E, then the magnetic bearing FROM Wallaroo would be 293°T – 7°E = 286°M.

When converting bearings ensure the answer obtained is a valid direction i.e. a value between 000° and 360°.

5.1.6.1 Back Bearing



Back bearing is the line measured backwards from the direction **an aircraft is flying to** a place over which it passed, without altering heading or airspeed.

Back bearing is measured clockwise from north. Any north reference can be used.

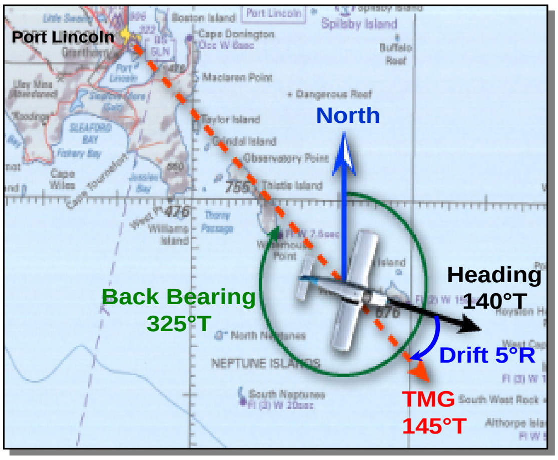
5.1.6.2 Calculating Drift using Back Bearing

Back bearing is useful to pilots because it is the reciprocal of the track made good. **Current drift** may be calculated in the following manner:

Example: An aircraft passed over Port Lincoln some time ago and has not changed heading (140°T) since. The back bearing obtained is 325°T.

The reciprocal of the back bearing equals TMG:

325°T – 180° = 145°T



An aircraft is drifting **from** heading **to** track or **from** heading **to** TMG when airborne. If the current heading is 140°T and the TMG is 145°T, the current drift is 5° Right.

5.1.6.3 Relative Bearing

Relative bearings are measured clockwise from the fore-aft axis of the aircraft and expressed in degrees from 000° to 360°. Relative bearings are by default TO type bearings, since they are measured at the aircraft's position and reflect the direction towards something external to the aircraft.

If required the reciprocal (FROM) of a relative bearing can be found by applying 180° in a similar way as with true or magnetic bearings:

- Add 180° when the relative bearing is 179° or less.

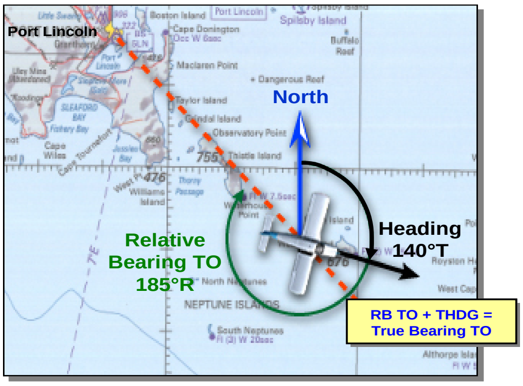
- Subtract 180° when the relative bearing is 180° or more.

Relative bearings can also be converted into either true or magnetic bearings, by adding the aircraft's heading to the relative bearing:

- Relative Bearing TO + True Heading = True Bearing TO.
- Relative Bearing TO + Magnetic Heading = Magnetic Bearing TO.

In the picture below the relative bearing TO Port Lincoln is 185°R (since the angle measured clockwise from the nose of the aircraft is 185° towards Port Lincoln).

The current heading is 140°T.



The true bearing TO Port Lincoln is:

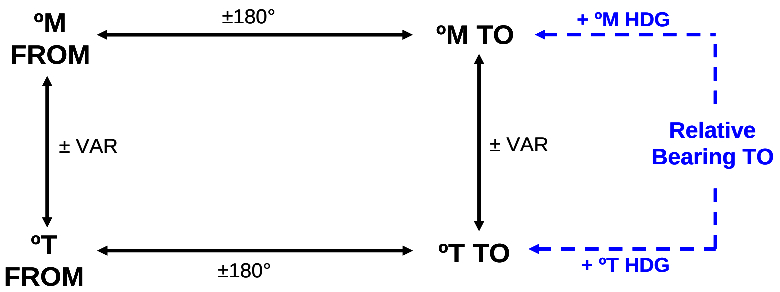
185°R TO + 140°THDG = 325°T TO.

It can be noted in this case that this would also be the back bearing to Port Lincoln, provided the aircraft passed over Port Lincoln and did not perform any heading changes since passing overhead.

As discussed previously the back bearing can be used to calculate drift and similarly the relative bearing TO a place the aircraft has passed over can be used to calculate drift:

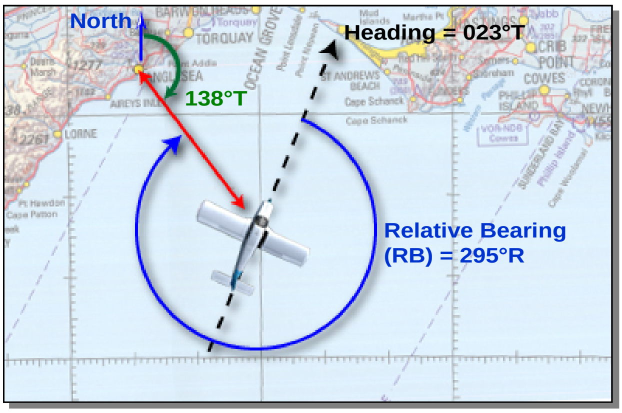
> ***Note:*** Relative Bearing >180° = Drift Right
> Relative Bearing <180° = Drift Left
>
> *The magnitude of the drift is the difference between the RB and 180º*

The following bearing conversion aid indicates the relationships between the various types of bearings and is useful in performing bearing conversions:



Relative bearings can also be used to find the aircraft's position on the map. To plot it for use on a chart, the true bearing FROM the fixed point is used.

In the example below, an aircraft flying a heading of 023°T locates a known feature on the map which bears 295°R. What bearing would the pilot plot from the feature to use as a position line?



True Bearing towards the town:	= RB TO + THDG = 295°R TO + 023°T = 318°T TO
Bearing to plot (FROM):	= 318°T TO – 180° = 138°T FROM

To establish the position of the aircraft, two or more bearings obtained simultaneously from different points would be required and ideally the angle of cut between these position lines should be as close to 90° as possible.

5.1.7 Ground-Speed (GS)

The ground speed of an aircraft is the speed at which it moves over the ground.

5.1.8 Airspeed

The airspeed of an aircraft is the speed measured relative **to the air mass** in which it is moving. There are three types of airspeed used in aviation and discussed in detail later in this chapter.

5.1.9 Ground Position

The position on the ground directly beneath an aircraft is known as its ground position.

5.1.10 Pin Point

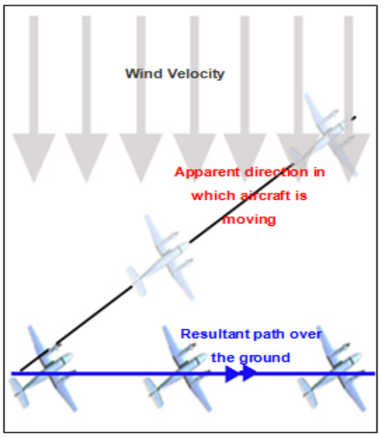
A pinpoint is the ground position of an aircraft obtained by direct visual observation.

5.1.11 Fix

A fix is the ground position of an aircraft obtained either by reference to the ground (a visual fix) or by radio-navigation aid indications (a radio fix).

5.2 Elements of the Velocity Triangle

5.2.1 Introduction



The basic navigational problem is that an aircraft does not necessarily fly over the ground in the direction in which it is pointing. A wind originating at an angle to the fore and aft of the axis of the aircraft tends to make it "crab" across the ground. In order to accurately plot the actual movement of the aircraft over the ground, various terms and concepts have to be clearly understood.

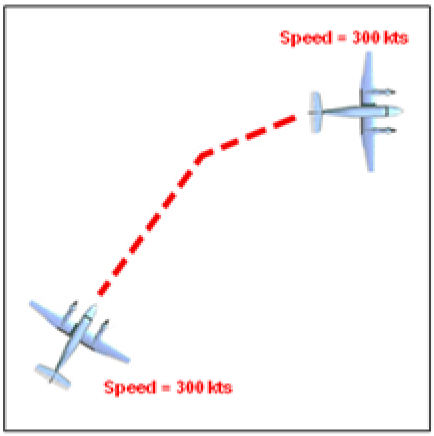
5.2.2 Speed and Velocity

The terms 'speed' and 'velocity' are often misused, as each have specific definition and cannot be interchanged.

5.2.2.1 <u>Speed</u>

Speed describes the rate at which an object is moving – and is termed a scalar quantity.

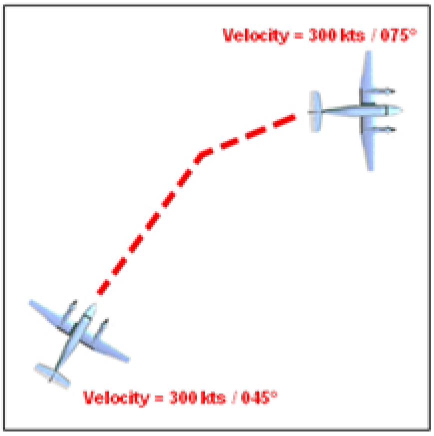
> **<u>Example</u>**: An aircraft is flying at 300 kts and changes direction, its speed will not change.



5.2.2.2 Velocity

Velocity describes speed in a specific direction – and is termed a vector quantity.

Example: An aircraft is flying at 300 kts in a direction 045° and changes direction to 075°, its velocity has changed.

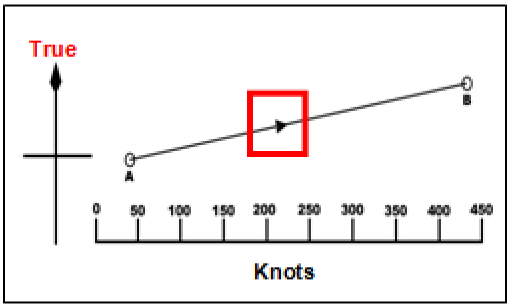


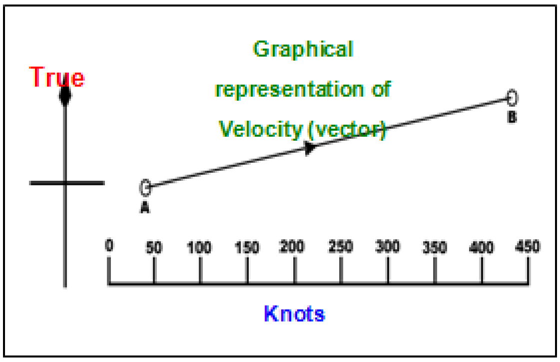
Speed describes an object with magnitude only.

Velocity describes an object with magnitude and direction.

5.2.3 Vectors

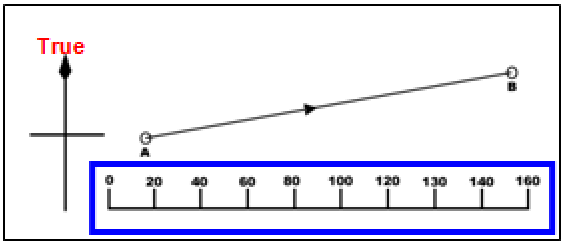
Since a velocity is a speed in a given direction, it is represented by a straight line. The length is proportional to speed, and direction, measured from an arbitrary datum line, is the same as the velocity.





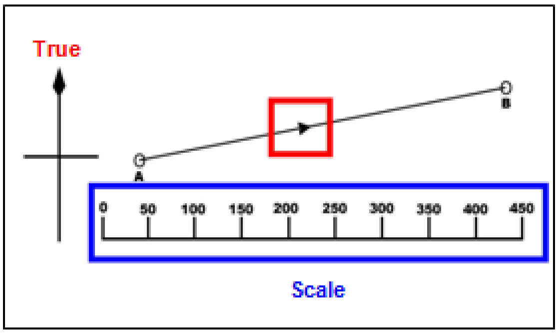
The straight line is called a vector.

The scale used in drawing vectors may be any that is convenient. The datum line for measurement of direction is by convention true north and points to the top of the sheet.



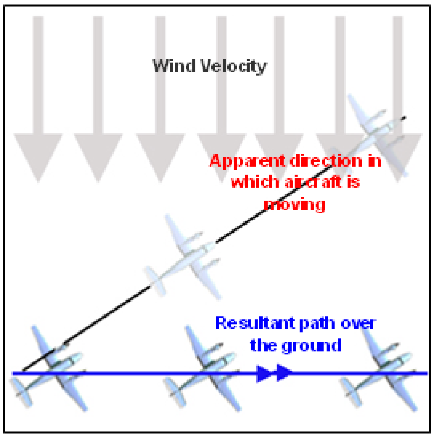
To represent the direction and scale of the vector insert the true north symbol at a point in the diagram and indicate scale by a graduated scale line.

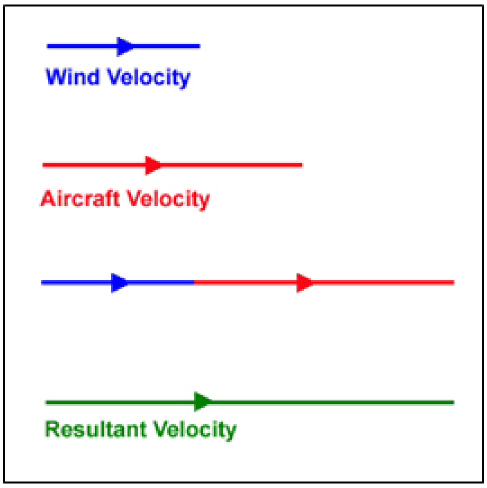
The diagram below illustrates the vector of an aircraft flying at 400 kts heading 085°T. The arrowhead indicates the sense of the vector presenting the direction as 085° and not 265°.



5.2.3.1 Vector Addition

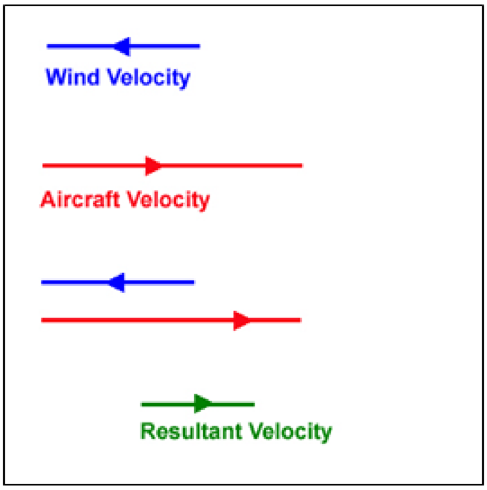
The diagram illustrates the basic navigation problem. The aircraft is moving through an air mass, which is moving. The resultant velocity of these two components determine the aircraft's path over the ground in terms of speed and direction.

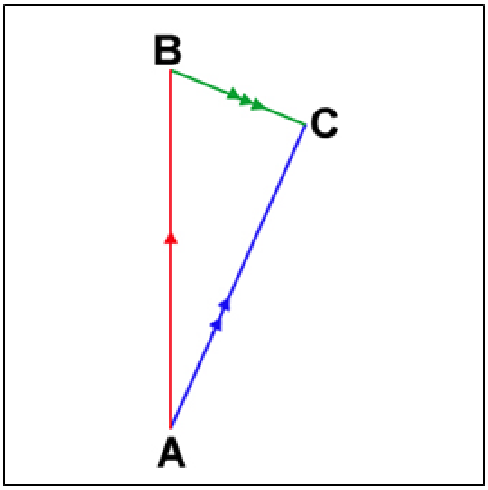




If the component velocities were acting in the same direction the resultant velocity is equal to the sum of the speeds in that direction.

Conversely, when the component velocities act in opposite directions the resultant velocity is the difference of the speeds acting in the direction of the greater component.

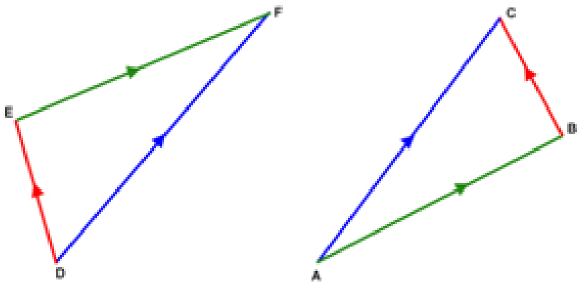




If the component velocities do not act in the same line the resultant velocity is an intermediate speed at an intermediate direction. Measure the resultant by constructing a vector diagram or triangle of velocities.

5.2.4 Components of the Triangle of Velocities

If the velocity vectors (AB or EF) and wind direction and speed (BC or DE) are drawn at the same scale, such that its sense arrows follow each other, then the resultant velocity vector is the third side (AC or DF).

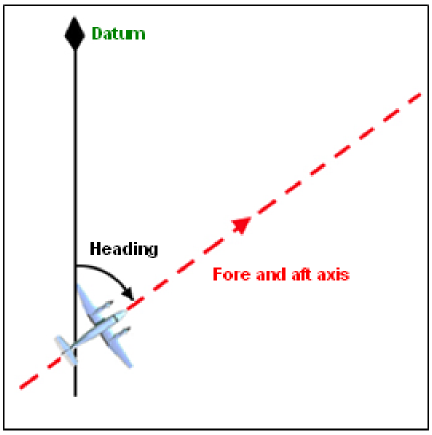


The sense of the vector is such that its arrow opposes the arrows of the component velocities around the triangle.

AC and DF are identical in magnitude and direction, it doesn't matter in which order the component vectors are drawn as long as its sense arrows follow each other.

5.2.4.1 Heading

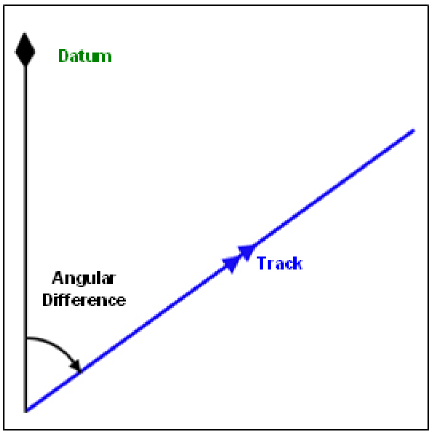
The heading of an aircraft is the angle in the horizontal plane measured clockwise from a datum line through the position of the aircraft and its fore and aft axis.



5.2.4.2 Track

The track is the path traced on the earth's surface by a point vertically below the aircraft.

The track at any point is the angle in the horizontal plane measured clockwise from the datum line through the point on the track and the track itself.



Note: It is often desirable to make a distinction between the track that an aircraft has already made (track made good), which may follow an irregular path, and a track that an aircraft hopes to follow (desired track or required track).

5.2.4.3 Wind Velocity

The combination of speed and direction of a wind is termed wind velocity (W/V) and is expressed as a five or six figure group (e.g. 090/45):

- Direction and speed are separated by an oblique stroke (/).
- Left of the oblique stroke, a value refers to wind **direction** (true direction from which it originated).
- Right of the oblique stroke, a value refers to wind **speed** (knots).

The velocity of a wind at 45 knots from the east is indicated as 090/45; and another of 145 knots with the same direction as 090/145. Wind is expressed in degrees true, the T (True) is omitted.

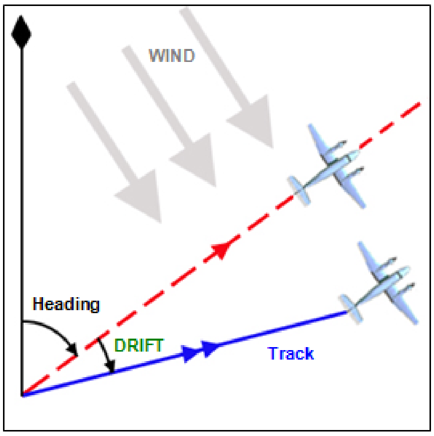
5.2.4.4 Drift Application

The angle between the heading and track is called **drift**.

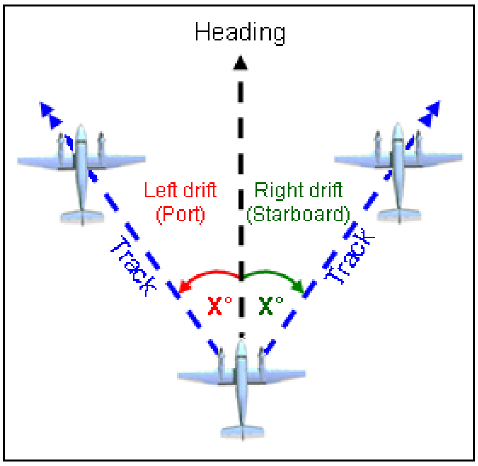
Drift is due to the effect of the wind and is the lateral movement imparted to an aircraft by the wind.

For an aircraft flying in conditions of no **wind** or directly upwind or downwind, the track and heading will coincide and there is no drift.

Under all other conditions track and heading will differ and the difference is referred to as **drift**.



Drift is expressed in degrees left (L) or degrees right (R) of the aircraft's heading. An aircraft experiencing left drift is said to drift **to the left** and track to the left of its heading. The phraseology "drift port" (P) or "drift starboard" (S) is sometimes used. Port drift is to the left and starboard drift to the right.

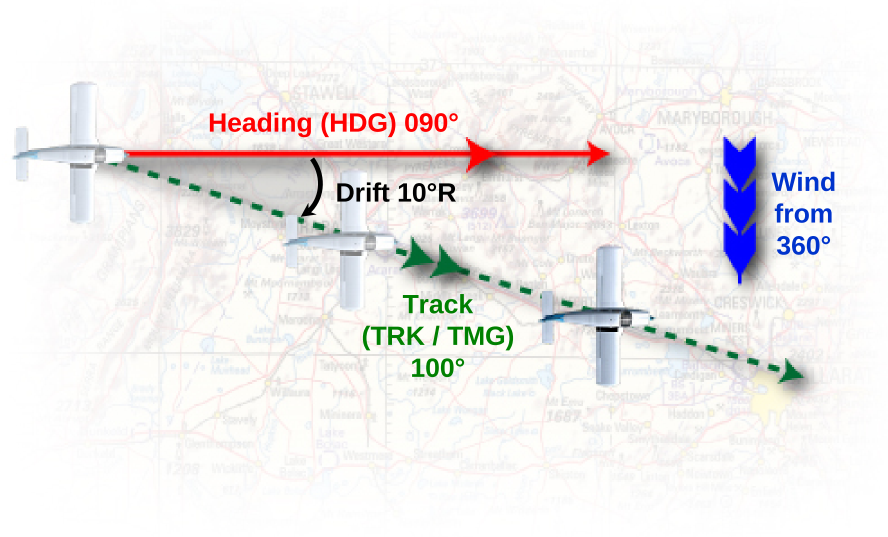


Current drift is measured by a variety of instruments, e.g. drift recorder, drift meter, etc.

Planning a flight, the FPT is measured on the chart and the wind velocity is obtained from a weather forecast. The drift is calculated from the track, TAS and wind velocity.

When the value of the drift angle is known it can be applied to the FPT to calculate the heading to steer to remain on the FPT. This enables the pilot to navigate the aircraft to the intended destination or waypoint along the chosen track, rather than letting the wind determine the track and take the aircraft in an undesired direction.

The planned track is measured as 100°T. The wind is from the North and drift calculated as 10°R:



If a track made good (TMG) of 100°T is required, drift needs to be countered by altering the aircraft's heading to 090°T (the aircraft steering 10°L into the wind) to counter the drift.

During the flight, a known drift value is applied to a known heading (obtained from the compass) to calculate the aircraft's TMG. This procedure is required to ensure that the aircraft is following along the intended path over the earth's surface and to calculate the corrections required to steer the aircraft back onto the FPT.

If the picture above is adapted to an in-flight example. The aircraft's heading is 090°T and the wind is from the North, therefore the aircraft will drift 10° towards the right. The resulting TMG will be 10° to the right of the heading:

090°T + 10° = 100°T.

5.2.5 Airspeed

The speed of an aircraft measured relatively to the air mass through which it is moving is termed airspeed. It is emphasised that due to wind velocity the speed may differ from that measured by an observer on the earth. Airspeed is independent of wind and is the same regardless of whether the aircraft is flying upwind or downwind. The three types of airspeed are as follow:

5.2.5.1 <u>Indicated Airspeed</u>

Indicated airspeed (IAS) is the reading of the aircraft's speed on the airspeed indicator (ASI).

IAS is used as reference during take-off, climb, approach and landing.

5.2.5.2 <u>Calibrated Airspeed</u>

Calibrated airspeed (CAS) is IAS corrected for instrument and position errors.

Aircraft may have different corrections, (i.e., only applicable to that particular aircraft). This correction is usually obtained from the aircraft's performance manual and is generally greater at slow airspeeds and negligible at higher (cruise) airspeeds. CAS is also referred to as rectified airspeed (RAS).

5.2.5.3 <u>True Airspeed</u>

The change to CAS, due to changes in temperature and pressure (density), it is referred to as True airspeed (TAS). TAS is the speed of the aircraft relative to undisturbed air.

TAS increases with altitude, although the IAS remains the same due to the reduction in air density with increasing altitude. TAS is calculated from CAS, pressure altitude and outside air temperature (OAT) by means of the navigation computer.

TAS can be estimated by adding 2% to the IAS for each 1,000ft of altitude. TAS is used in various navigation calculations during flight planning and solving the velocity triangle.

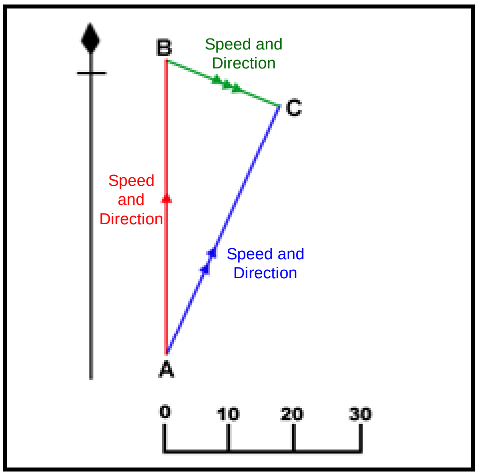
5.2.5.4 Ground Speed

Since air navigation is concerned with the movement of an aircraft along the earth's surface, the speed of the aircraft relative to the surface is of importance. This is termed ground speed and measured in knots (nautical miles per hour). Ground speed is derived from TAS by applying the headwind- or tailwind velocity affecting the aircraft. Headwind is subtracted from TAS and tailwind added to TAS to calculate ground speed.

5.3 Solving the Triangle of Velocities

5.3.1 Introduction

The triangle of velocities is said to consist of three components (vectors), each representing a speed and direction.



Knowledge of any two components solves the remaining component. In navigation, two problems solved by this method are:

- Measure the length and direction of one side, e.g. finding track and ground speed, wind velocity, heading and airspeed.
- Measure the length of one side and the direction of another, e.g. true heading and ground speed.

The triangle of velocities can be solved by means of:

- Plotting or scaled drawing
- Navigation computer (Chapter 6 - CR3 Wind Side)
- Mathematically using trigonometry.

5.3.2 Solving the Triangle of Velocities by Plotting

5.3.2.1 Rules for Plotting

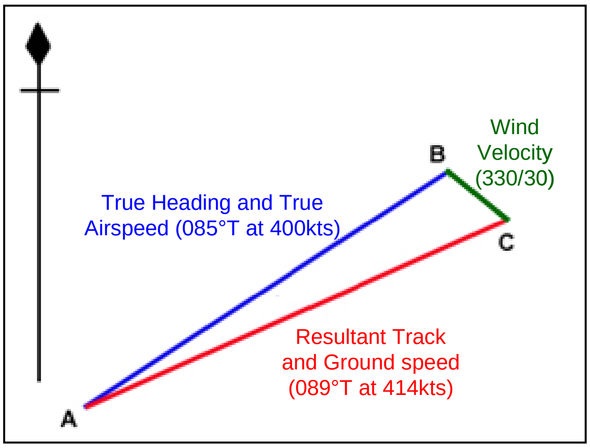
Of importance when plotting the vector triangle:

- The same datum (North) direction and a uniform unit of measurement (scale) must be used for all vectors, preventing the diagram being distorted.
- Ensure that each component (vector) of the velocity triangle is correctly represented; true airspeed is measured along heading; ground speed is measured along track and wind velocity is drawn from the heading towards the track, represented by its speed and direction.

5.3.2.2 Arrow Convention

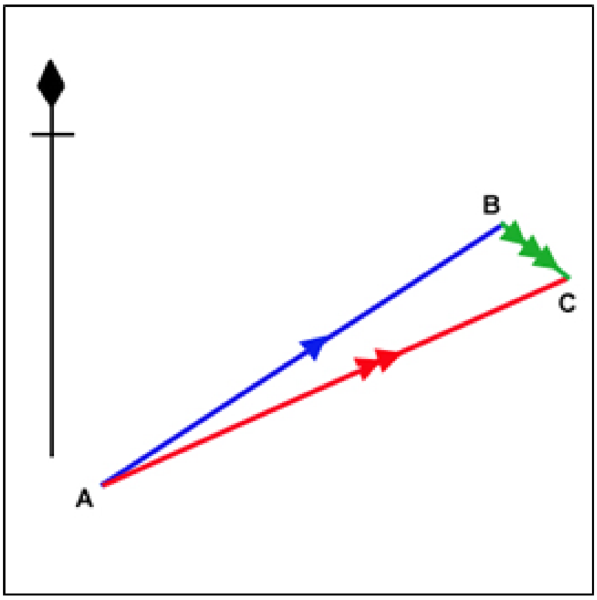
The vectors in the diagram have been labelled, i.e. navigational components of the triangle of velocities are shown.

In practice this labelling would be clumsy and tedious. Therefore, a convention of arrows has been adopted.



The same triangle is illustrated with arrows identify each vector:

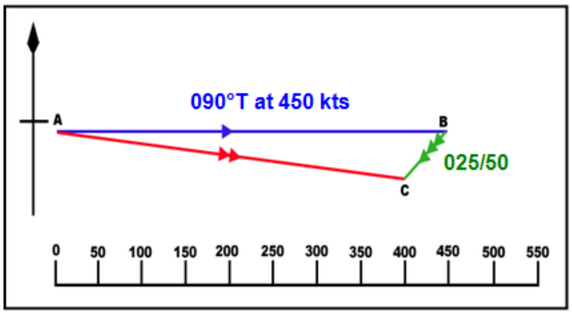
- The true heading and true airspeed vector (air vector) caries one arrow (A-B), pointing in the direction of the heading.
- The true track and ground speed vector (ground vector) carries two arrows (A-C), pointing in the direction of the track.
- The wind velocity vector (wind vector) carries three arrows (B-C) pointing in the direction the wind is blowing to.



5.3.2.3 Finding Track and Ground Speed

An aircraft with TAS of 450 kts on a heading of 090°T, experiences a W/V of 025/50. What is the track and ground speed?

Solution:

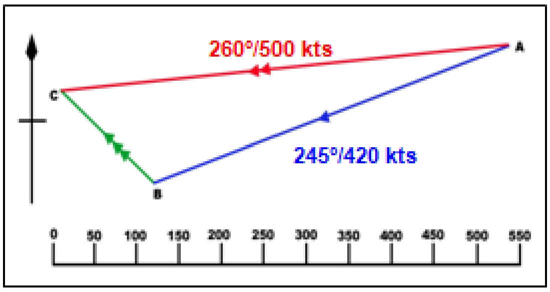


- Plot the air vector **AB** (heading and TAS).
- From B lay-off the wind vector **BC**.
- Join **AC** and measure the ground vector's direction and length. Track and ground speed are found to be 096°T and 432 kts.
- Drift is calculated by comparing the heading 090°T and the track 096°T. 096° - 090° = 6°R. (the ground vector is to the right of the air vector)

5.3.2.4 Finding Wind Velocity

The ground speed of an aircraft is 500 kts on a track of 260°T; its true airspeed is 420 kts on a heading of 245°T. What is the wind velocity?

Solution:



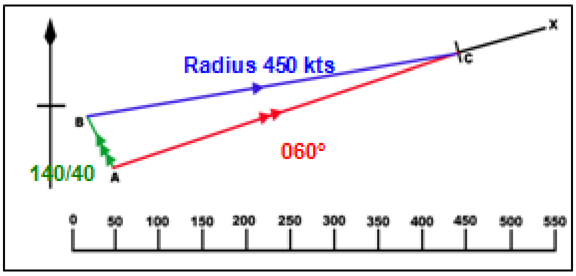
- Plot the air vector **AB** (heading and true airspeed).
- From A plot the ground vector **AC** (track and ground speed).
- Join **BC** and measure its direction and length. Wind velocity is measured as 129°T/144kts (W/V is from heading to track or air- to ground vector).
- Drift is calculated by comparing heading and track, 260°T - 245°T = 15°R (the ground vector is to the right of the air vector) .

5.3.2.5 Finding Heading and Ground Speed

The determination of the heading to make good a given track and the resultant ground speed, is probably the most common navigation problem and the method to solve the velocity triangle during pre-flight planning.

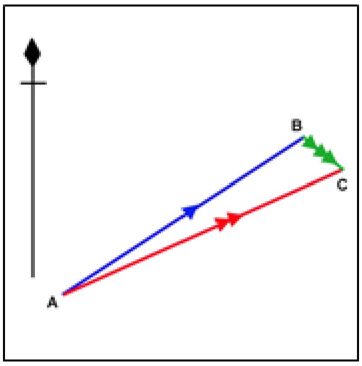
A pilot in an aircraft with a true airspeed of 450 kts wishes to make good a track of 060°T, the wind velocity is 140/40. Calculate the heading to be flown and ground speed?

Solution:



- Draw a line **AX** of indefinite length in a direction 060°T to represent the required track.
- From A lay-off with the wind vector **AB** (drawn down-wind).
- Draw and arc, measuring the value of the TAS, from B to pass **AX** at **C**.
- The direction of **BC**, 065°T, is the heading required to make good a track of 060°T. **AC** represents ground speed 441kts.
- The drift is calculated by comparing the heading to the track, 065°T - 060°T = 5°L (the ground vector is to the left of the air vector).

5.3.3 Runway Wind Components



The ideal situation is to have the wind blowing parallel to the runway and the aircraft taking off or landing into wind.

Taking off into wind has the advantage of shortening the takeoff ground roll distance in terms of the amount of runway required to become airborne. Landing into wind shortens the landing ground roll, thereby reducing the amount of runway required to land.

Whilst the wind direction is not parallel with the runway centreline direction it is necessary to determine:

- The headwind component (HWC) or tailwind component (TWC) in the direction of the runway.
- The crosswind component (CWC) perpendicular to the runway.

Each aircraft has a crosswind limit, which must not be exceeded, which affect the controllability of an aircraft during take-off and landing. When the crosswind component exceeds this limit a take-off or landing should not be attempted.

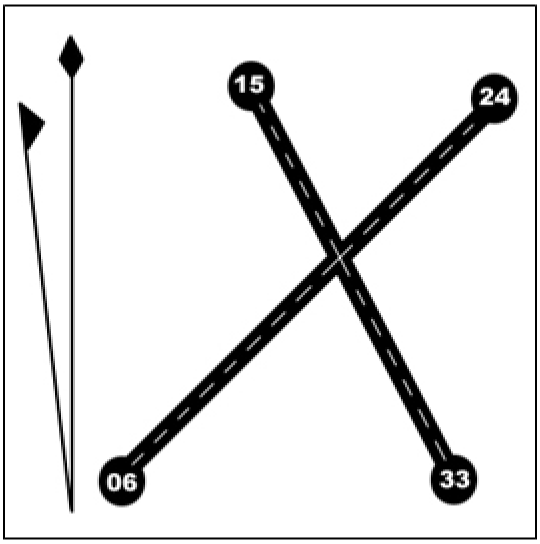
The wind velocity vector must be resolved into two components at right angles to each other. The values of the components may be deduced:

- Graphically
- Mathematically by using trigonometry
- A wind component table
- The navigation computer (Chapter 6 - CR3 Wind Side).

Example: The surface wind is 080°T at 30 kts (180/30). Calculate the wind components across and along runway 06, the variation is 7°W.

Note:
The runways at an aerodrome are identified by the first two digits of the runway direction, e.g., runway 06 has a centreline direction of 060°M and runway 24 (the other threshold) has a centreline direction of 240°M.

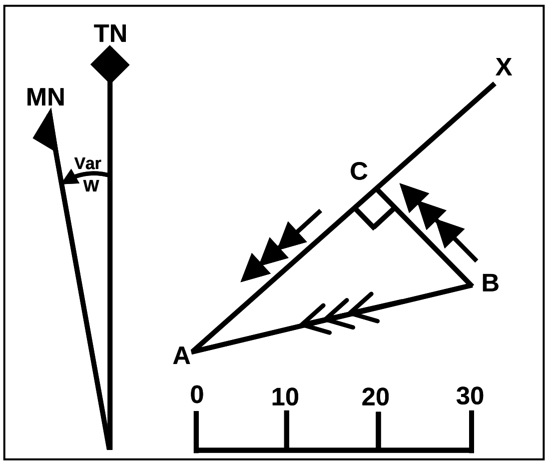
Runway centreline directions don't always exactly match this convention. Always consult the Jeppesen Airport Directory or Terminal section for the runway layout and centreline direction.



5.3.3.1 Graphical Solution

The true direction along runway 06, 060°M - 7°W variation = 053°T.

- The north reference is in degrees True. It could also have been constructed in degrees magnetic, as long as all the vectors are in magnetic.
- Draw ground vector **AX** (along C) of indefinite length in the direction of the runway centreline, i.e. 053°T.



- Draw **AB** represents the scaled wind at 080/30. Draw the wind vector (**AB**) 080°T to the runway (**AX**), intersecting at A.
- Draw **BC** perpendicular to **AX**. **BC** represents the crosswind component, The magnitude can be measured using the wind velocity scale. The crosswind component (**BC**) is 14kts.
- **AC** represents the headwind along the runway centreline. The length of the headwind component is measured along **AC,** as 27kts.

5.3.3.2 <u>Trigonometrical Solution</u>

The wind vector (**AB**) is from 080°T and the runway centreline (**AC**) 053°T. The offset angle between the runway (**AC**) and the wind vector (**AB**) is 27°. .

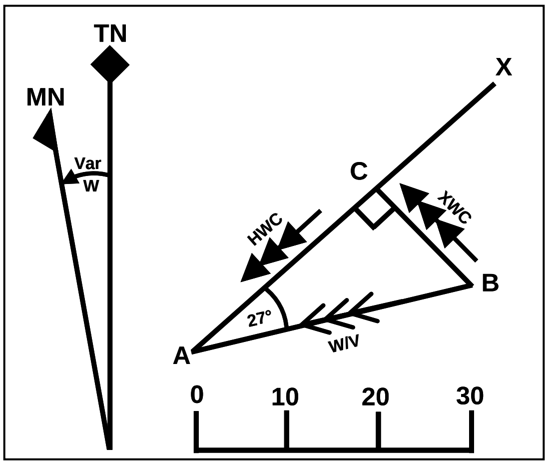
From Δ ACB, as ACB is a right angle:

- Headwind component:

  AC = 30 cos 27° = 26.7 kts

- Crosswind component:

  CB = 30 sin 27° = 13.6 kts



5.3.3.3 <u>Wind Component Tables</u>

Graphically solving wind components is a time consuming exercise, therefore standard tables have been compiled, based on the angle between wind direction and runway heading, providing the amount of headwind, tailwind and crosswind component for a known wind speed.

WIND COMPONENT TABLES

WIND SPEED KNOTS	ANGLE BETWEEN WIND DIRECTION AND HEADING (LEFT OR RIGHT)							
	10	20	30	40	50	60	70	80
	HEADWIND COMPONENT							
5	-5	-5	-4	-4	-3	-3	-2	-1
10	-10	-9	-9	-8	-6	-5	-3	-2
15	-15	-14	-13	-11	-10	-8	-5	-3
20	-20	-19	-17	-15	-13	-10	-7	-3
25	-25	-23	-22	-19	-16	-13	-9	-4
30	-29	-28	-26	-23	-19	-15	-10	-5
35	-34	-33	-30	-27	-22	-18	-12	-6
40	-39	-38	-35	-31	-26	-20	-14	-7
45	-44	-42	-39	-34	-29	-23	-15	-8
50	-49	-47	-43	-38	-32	-25	-17	-9
55	-54	-52	-48	-42	-35	-28	-19	-9
60	-59	-56	-52	-46	-39	-30	-21	-10
65	-64	-61	-56	-50	-42	-33	-22	-11
70	-69	-66	-61	-54	-45	-35	-24	-12

Wind component tables are listed in the Tables and Codes section (p5-6) of the Australian Jeppesen.

To reference the table the wind speed and offset angle between the wind velocity and the runway direction must be known.

Example: An aircraft is cleared to land runway 04 (035°M). The surface wind is reported as 075°M at 30 kts (075M/30). Determine the crosswind component

Solution:

- Enter at the top of the table in the column corresponding to the offset angle, 075°M -035°M = 40°
- Find the wind speed in the left column (Wind Speed Knots), continue along the row to the offset angle column, 40°.
- For values between listed offset angles or wind speeds, interpolate.as required.

WIND SPEED KNOTS	ANGLE BETWEEN WIND DIRECTION AND HEADING (LEFT OR RIGHT)							
	10	20	30	40	50	60	70	80
	CROSSWIND COMPONENT							
5	1	2	3	3	4	4	5	5
10	2	3	5	6	8	9	9	10
15	3	5	8	10	11	13	14	15
20	3	7	10	13	15	17	19	20
25	4	9	13	16	19	22	23	25
30	5	10	15	19	23	26	28	29
35	6	12	18	22	27	30	33	34
40	7	14	20	26	31	35	38	39
45	8	15	23	29	34	39	42	44
50	9	17	25	32	38	43	47	49
55	9	19	28	35	42	48	52	54
60	10	21	30	39	46	52	56	59
65	11	22	33	42	50	56	61	64
70	12	24	35	45	54	61	66	69