LONG-RANGE NAVIGATION WITH LIMITED FACILITIES

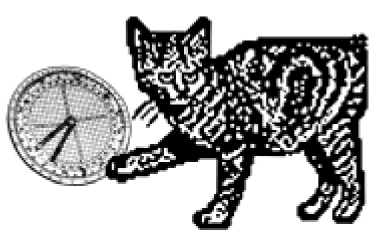
Some notes to help you get across those vast empty oceans, using only the facilities of Flight Simulator that were available immediately Post-War.

In practice, this means just using Non-Directional Beacons and Dead Reckoning.

Compiled for DC3 Airways

by

Peter Tucker



When we limit ourselves to Flight Sim. radio facilities that were available in the 1950s, we are really making things doubly difficult for ourselves – once by discarding all the more modern navigational aids, and twice, by not having in Flight Simulator some of the facilities that were available fifty years ago, and are not around any more - neither can we take sun and star shots, or get bearings from long range broadcasting stations.

However, we have our NDBs, and very useful they are too, and not to be thought of as poor substitutes for a VOR!

This set of notes tries to shed light on some of the problems that may arise in a long flight, out of range of navigational beacons.

1. The ADF or Radio Compass
2. Using NDBs.
3. The Triangle of Velocities
4. Great Circles and Rhumb Lines
5. FS Navigator Great Circle Routes
6. Magnetic North

1. Automatic Direction Finder (ADF), or Radio Compass

This equipment enables a pilot to determine the direction, relative to the aircraft, from which radio signals are being received.
These signals may be from aeronautical beacons, or from broadcast stations.
The range will vary according to the power of the transmitter, which in turn depends on the purpose for which it has been provided, but is typically in the region of 10 – 100 nm.
Airways beacons would have a greater range than those near airports intended to guide aircraft to a particular runway approach.

The equipment is called "Automatic" as it has replaced the original designs that required a loop aerial to be turned manually to detect a null in reception.
These loop aerials may be seen in many photographs of wartime aircraft, either as simple circular loops, or encased in streamlined fairings.
In the case of the DC3, it is generally found under the nose behind the pitot tube, or sometimes above the fuselage just behind the cockpit.

Since a loop aerial has a "figure-of-eight" response, it produces two nulls, 180 degrees apart, and a means had to be found to identify which of the two bearings was the required direction to the transmitter.
This was done by electrically adding in the signal from a fixed non-directional aerial, giving a "cardioid" or heart-shaped response – with only one null.

In the ADF, all this is done automatically, and the instrument has a 360-degree scale, with zero representing the nose of the aircraft, and a needle pointing in the relative direction of the transmitter.

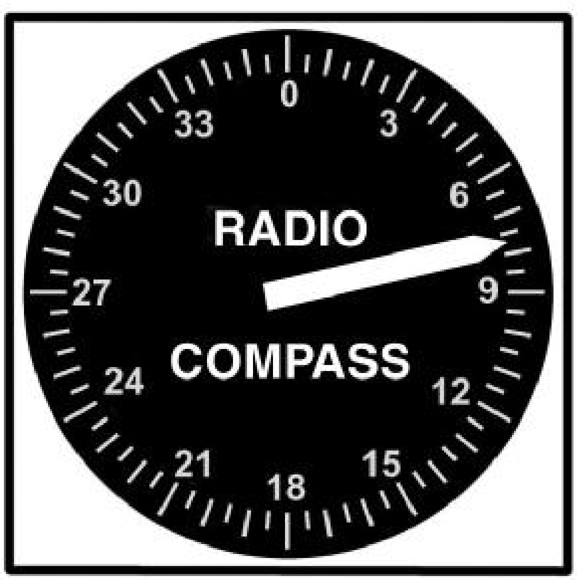


Fig. 1

2. Radio Navigation, using the ADF and NDBs
Finding your direction from non-directional beacons.

If there were no winds, aircraft navigation would be no problem at all; you'd just point the aircraft in the direction that you wanted to go, and sooner or later – you'd get there! But life's not like that.

Except on rare occasions, the air that you fly in is continually moving; and it's not all moving at the same speed, or in the same direction – and at different heights above the ground, it could all be different again.
Consequently, if you point the aircraft in the direction that you want to go, without any thought for the effect of the wind, it is very unlikely that you'll actually get there!
The difference in direction between where the aircraft is ***Heading***, and the actual ***Track*** that it follows over the ground is called the ***Drift.***

When you are flying over countryside with plenty of landmarks that you may know well, or over short distances, this does not matter too much. You simply adjust the heading of the aircraft a bit, to compensate for the drift, and all is well.
However, if you are flying long distances; over the sea, or over terrain with few recognisable landmarks; then the speed and direction of the wind has a significant effect on the flight-path of the aircraft. You can no longer just point the aircraft in the direction that you want to go, and expect to arrive at your destination.

In fast modern aircraft, the effect that the wind has on navigation is reduced, in proportion to the speed of the aircraft, and modern aircraft have sophisticated electronic navigational devices to tell the pilot exactly where he is at any time.
Going back to the first days of the DC3, though, it was quite a different matter.
While on certain routes there were a number of airway markers, with their Morse "N" and "A" sectors to tell you if you were on track, and the famous "Cone of Silence" overhead the beacon, they were not nearly as accurate and sophisticated as the VOR beacons that we take for granted today.

If we try to navigate in Flight Simulator without using the more modern VORs, which tell you what direction you are from the beacon, and if you are to left or right of track or exactly on course, we are left with just the NDBs, or Non-Directional Beacons.
This is not too bad if we want to fly towards the beacon. All we would have to do would be to keep the needle of the ADF pointing directly ahead, and we would eventually reach the beacon.
This isn't the most efficient way, though, if there is a crosswind, as the aircraft would be blown to one side, and approach the beacon in a curved path.

But this isn't as bad as when we want to fly away from the beacon in a particular direction, when the next beacon is still out of range. Whatever direction we fly in, all the needle indicates is that the beacon is behind us, which isn't much help!
(It's a bit like the case of being at the South Pole, when whatever direction you go in, it is always North.) This is when you wish you had a VOR.
But things aren't really as bad as all that, because all we have to do is add in our compass bearing, and then the information from the Radio Compass can tell us if we are on track or not, almost as well as the VOR can.

There are a number of problems that may occur when using NDBs and the ADF alone, for the Trans-Atlantic Charter, and other long-distance flights:

1. How to approach the next beacon in a straight line, in an unknown wind.
2. How to find the QDM to a beacon
3. How to find, and fly, a specific QDM to a beacon
4. How to fly a specific QDR from a beacon.

Situation 1.

You want to fly to a particular beacon.
You aren't too worried that you fly exactly along a particular track, but you want to fly straight there, without being blown into a curving path by a strong crosswind.

This one is simple, but involves a little bit of trial and error.

a. Head directly for the beacon.
The ADF needle will point to zero – straight ahead.

b. Keep flying on a constant heading, and note if the needle starts to move to the left or the right.
(If it keeps to a steady zero, there is no crosswind component, of course, so just keep on the same heading until you reach the beacon).

c. If the needle swings to the left, it means that you have a crosswind component from the left, so turn the aircraft TO the left, into the wind by, say, ten degrees. (If you have a crosswind from the right, of course, all the following directions are reversed.)
(It is not possible to tell directly what the angle of drift is – how quickly the needle swings left or right depends on how far away the beacon is. If you are quite close to the beacon the needle will swing quicker than if it is further away.)

d. The beacon should now be to the right of your heading. Keep flying this new heading, and see if the needle – which will also now be pointing to the right of the aircraft – continues to move to the left, stays steady, or starts to swing to the right.

e. If the needle is still swinging to the left, turn the aircraft even more into the wind with a further left turn. If the needle has started to swing to the right, decrease the amount of left correction. The result that we want is for the needle to show a constant reading – either left or right – when we fly on a steady heading.

f. With the needle keeping a constant reading, we are then travelling in a straight line towards the beacon. The angle between the needle and straight ahead is our drift angle, either left or right.

g. As you approach the beacon, the needle will get more and more sensitive, and will almost certainly start to drift left or right. If it does, just put in a little bit more, or less, correction to stop the needle swinging, until the needle moves so quickly that you must be almost over the top of the beacon. When it does this, don't try to chase the last quick movements; fly a steady course until the needle swings to the tail of the aircraft, indicating that the beacon is now behind you.

(The equivalent action with a VOR would be to rotate the Omni-Bearing Selector until the left-right needle centres, with a "TO" indication; turn onto the same heading, and by making small adjustments to that heading, fly to keep the needle centred; the "TO" turning to a "FROM" as the beacon is over-flown.)

Situation 2.

You want to find the Magnetic heading to be steered by the aircraft (in conditions of no wind) to reach the next NDB – the QDM.

This is simply found by adding the Magnetic Heading of the aircraft to the Radio Compass reading. (If the sum of the two angles adds up to more than 360 deg., subtract 360 deg. to get the QDM.)

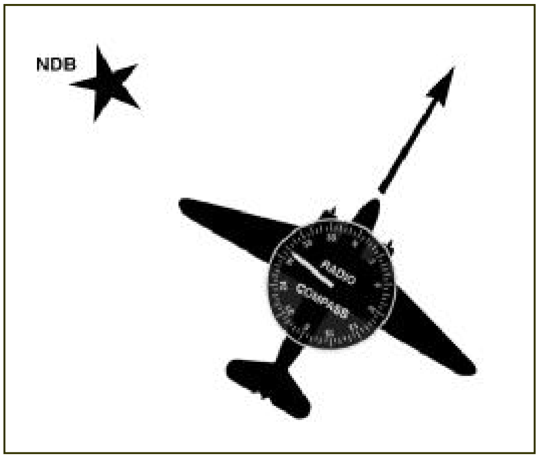


Fig.2

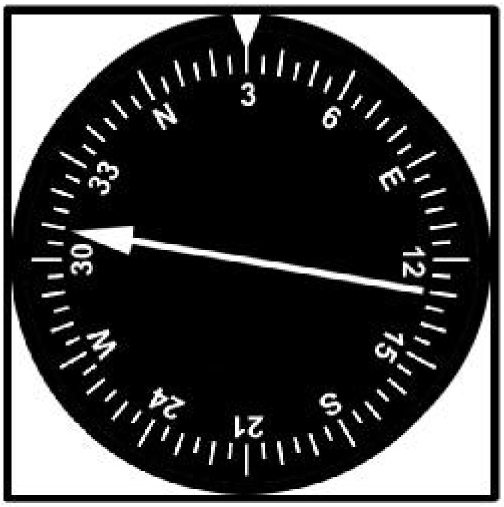
Example:

Aircraft heading	030º M.
Radio Compass	280º
QDM	310º

If the aircraft is fitted with a **Radio Magnetic Indicator (RMI),** the two indications are combined in the one instrument; and the QDM may be read off directly.

(The equivalent action with a VOR would be to rotate the OBS until the left-right needle centres, with a "TO" indication; and read the bearing directly from the scale.)

The RMI has a rotating compass scale, driven by the aircraft's distant reading compass, and superimposed on this background is a standard ADF pointer.
There may in fact be a second ADF or VOR pointer, so that two QDMs may be plotted at the same time, giving a simultaneous fix.



The default Cessnas in FS2000 and 2002, and the FS2000 Company DC3, have an instrument that is halfway between the simple Radio Compass and the RMI, in that there is a rotating scale at the back, but it is not driven by the compass. There is, however, a setting knob that you can use to synchronise it with the compass reading, and having done that, you can then read off the QDM directly.

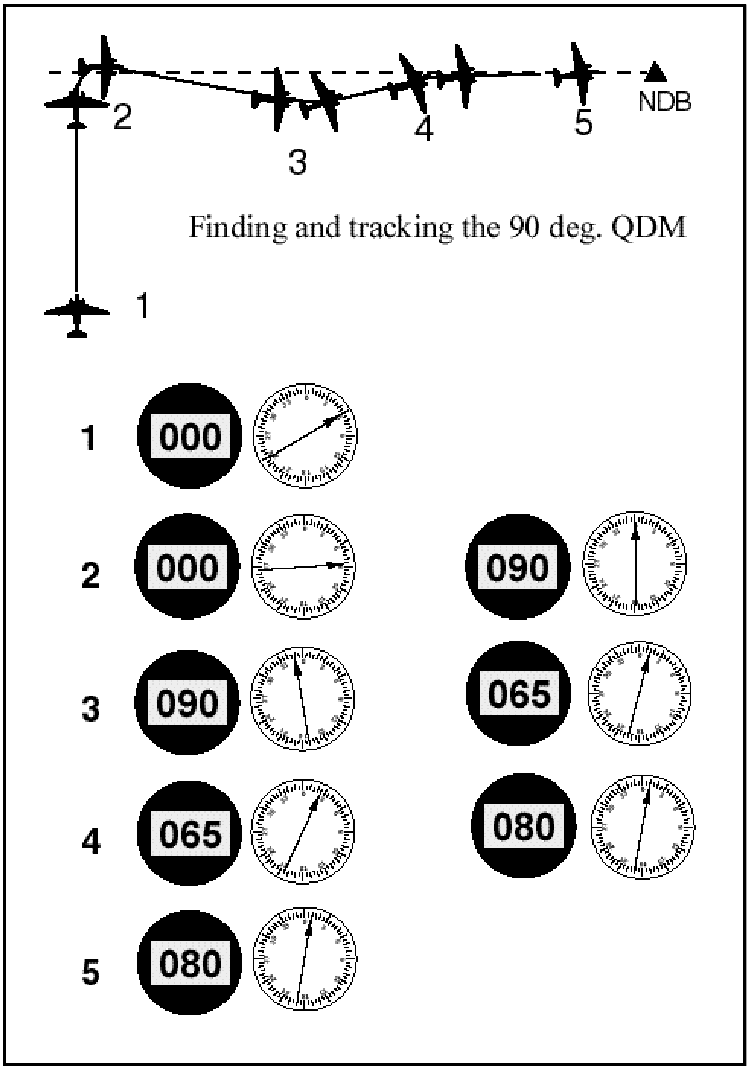
Fig. 3 The Radio Magnetic Indicator showing the same situation as in Fig.2

Situation 3.

You want to intercept, and follow, a specific QDM to the beacon.
At any time you can find your current QDM to the beacon, by adding the Radio Compass reading to your present heading.

Check your QDM, and get a mental picture of where you are in relation to the beacon. Choose a course that will intercept the required QDM.

Subtract your heading from the required QDM, and when the ADF shows this figure, turn for the beacon, and follow it, adjusting for any drift as in example 1.
Watch the ADF reading, and if it changes, make an adjustment to the heading so that the two readings add up to the required QDM.
You should aim for a steady reading of the Radio Compass, with, for example a reading of 10 deg. to the left balanced by a heading 10 deg to the right of the required track. The 10 Left and the 10 Right cancel out, putting you on track.



Finding and tracking the 90 deg. QDM

1. The aircraft is heading North to intercept the 090 QDM. It can be seen, by adding the heading of 000 to the ADF reading of 060, that it is currently on the 060 QDM. It continues on its present heading, and will be on the required QDM of 090 when the ADF reads 090.

2. The ADF is now reading nearly 090 and the aircraft starts a turn onto a heading of 090. It is now on the required QDM.

3. A wind blowing from the North has put the aircraft to the South of the required QDM. Although the heading is still 090, the ADF reading is now 350. The aircraft turns 25 deg. to Port, to regain the required Track The heading becomes 065, and the ADF reads 015

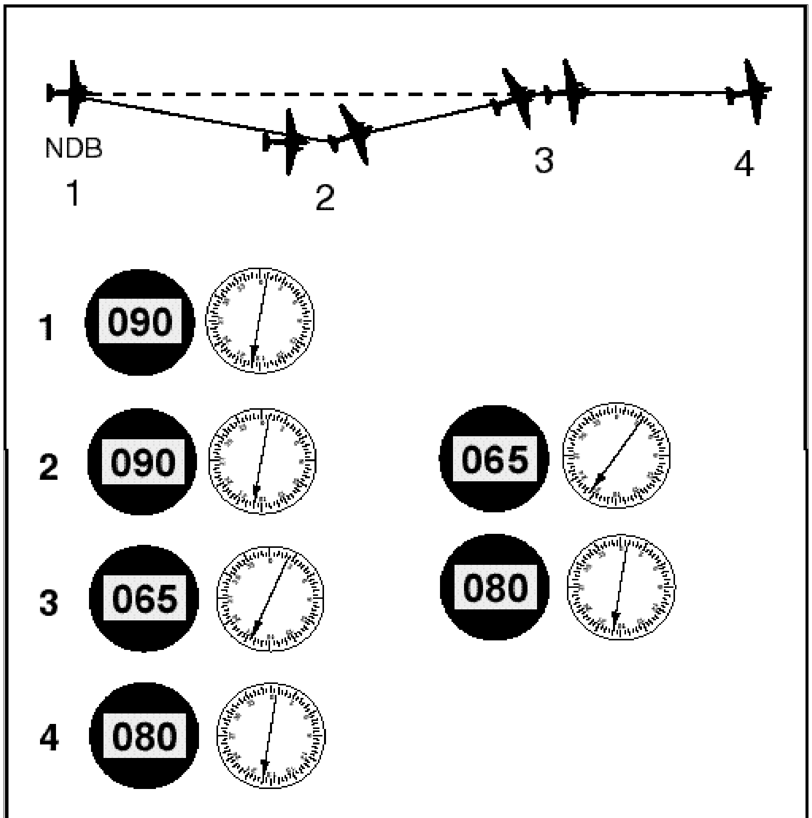
4. The aircraft is back on track, as can be seen by adding the Heading of 065 to the ADF reading of 025, which gives the required QDM of 090.

If the aircraft continued on this heading it would be over-correcting for drift, and would fly to the left of track. By means of "trial and error" it turns right 15 deg. to a heading of 080. The ADF reading is now 010 .

5. It is now flying 10 deg. to left of the required QDM direction, and the ADF is reading 10 deg. to the right, and with these two readings remaining steady, the aircraft will track correctly along the 090 QDM. Small corrections may have to be made, particularly as the aircraft nears the beacon, to keep the two readings balanced. As long as the Heading plus the ADF reading add up to 090, the aircraft will be on track.

Situation 4.

You want to leave a beacon, flying along a particular track.
This is very similar to the previous situation, but the sum of the aircraft heading and ADF readings should add up to the reciprocal of the track. (Add, or subtract, 180 deg.) One advantage in this situation, though, is that if the aircraft initially flies over the beacon, heading directly for the next turning point, if there is a crosswind, the drift will show up on the ADF straight away. A correction can be applied into wind, and the required track should be maintained without too much difficulty.



Finding and tracking the 90 deg. QDR

1. The aircraft flies over the NDB, on a heading of 090 deg.
   The ADF swings round and points astern – settling after a minute or two on a reading of 190.

2. The crosswind from the North has put the aircraft south of track.
   Heading 090 deg., ADF 190.
   The aircraft is on the 280 QDM: (90 + 190), which gives a QDR of 100 deg.(The reciprocal of 280)
   The aircraft turns left 25 deg., to regain track, now heading 065 deg., ADF 215.

3. Back on track, heading 065 deg., ADF 205. Adding 65 to 205 gives the sum of 270. The reciprocal of this is 090, the required QDR.

   An easier way to look at this is :
   We are heading 25 degrees to the left of track, and the ADF is showing 25 deg. to the left of dead astern – the two readings balance, so we are on track.
   If we continued on this heading we would over-correct for the drift, so by trial-and-error we turn 15 deg. to the right. The heading is now 080 deg. and the ADF 190.
   With the heading 10 deg. to left of track, and the ADF 10 deg. to left of dead astern, the readings are balanced, and we are still on track.

4. Keep watching the heading and ADF, and maintain a balance between the two.
   The ADF readings will become less sensitive to slight fluctuations the further away from the beacon you get. Find the heading that balances the ADF reading, so that by the time you get out of range of the beacon, you are confident that you have correctly compensated for drift, and are right on track.
   Maintain your heading until the next NDB comes into range, which should then hopefully appear dead ahead.

3. Air Navigation and the Triangle of Velocities

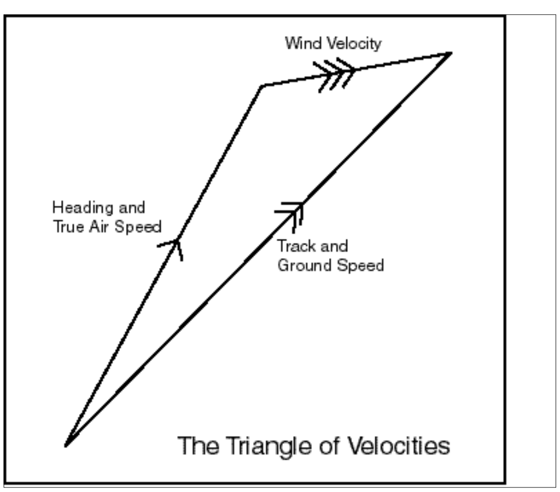
Don't go round in circles – use triangles!

"Velocity" is not the same as "Speed".
Speed is a Scalar property – it just has a Magnitude, like pounds, kilograms, miles or kilometres.
Velocity is a Vector property; in other words it has a Magnitude AND a Direction, like another vector property – Force.
If we talk about the Wind Velocity, we mean Wind Speed and Wind Direction – both properties taken together.

Most units of measurement are Scalar – and if you want to add two amounts of them together – you just add them up of course, in the usual way;
2 gallons of fuel, plus 5 gallons of fuel equals 7 gallons of fuel…
Not so with Vectors.
You have to take into account the magnitude and direction of the two units being added; and to do this, the easiest way is to draw a vector diagram.

If you draw two lines with lengths in proportion to the magnitudes of the vectors, and in the directions of the two vectors, joined nose to tail; the sum of the two vectors, is represented in scale and direction by the line joining the two extremities, forming a triangle.
Thus two vectors can be added together to produce a third, or resultant, vector.
These three vectors have a total of six variables, but if we know any four of them, we can work out the two unknown values.

In the case of Velocities, the diagram is called the Triangle of Velocities, and is the basis of all the hand-held mechanical computers used by pilots since before the Second World War – decades before a "computer" meant something electronic.
(Other related problems such as working out speeds from distances and times, fuel consumption, and conversions, etc., can be solved by using the circular slide rule on the back of the instrument.)
In those days, if you had a Navigator with a plotting table, he would draw the triangle to scale on his charts, as the flight progressed, but for single-seater aircraft the pilot had to work out the problem in an easier way, and this led to the development of a range of devices with swinging arms, sliding scales or rolling belts – all recreating the triangle of velocities.



The three velocities are:

1. Aircraft Heading, and Airspeed
2. Wind Direction and Speed
3. Aircraft Track, and Ground Speed.

The wind always blows you
FROM your HEADING vector
TO your TRACK vector.

(N.B. To avoid confusion, the number of arrowheads
on each side follows the convention as shown

I have tried to avoid the use of the term "Course", as this also could lead to a misunderstanding, and stuck to "Heading" – literally the direction the aircraft is pointing, or Heading, and "Track" – the direction of the path of the aircraft over the ground – if it trailed a rope behind it, it might leave an actual "track" on the ground.

"Track" may refer to the intended or required track from your departure point to your destination, or to the actual track of the aircraft, which through incorrect allowance for the wind, may not be exactly the same as the required track.

Two of the properties in the Triangle of Velocities are generally under the control of the pilot – **Heading** and **Airspeed**
Two are left to Nature **–** **Wind Speed** and **Direction**, and the resultant of these defines its **Track**, or the direction that the aircraft travels over the ground, and **Ground Speed**, or the speed of its progress over the ground.

It is therefore up to the pilot to choose a Heading that will give the required Track.
The Airspeed is generally set at the cruising speed for the particular aircraft, as shown in the aircraft's handling notes, but the resulting ground speed defines the duration of the flight, and how much fuel will be required.

At the Flight Planning stage, a forecast wind should be available, and knowing the aircraft's cruising speed, and the Required Track to the destination, the two unknown properties would be Heading and Ground Speed.

Using the calculator, or actually drawing the triangle of velocities would give the Heading to be flown, and an estimated Ground Speed. This would give an Estimated Time of Arrival at the destination, or first turning point.

The first leg of the journey is then flown, following the Heading worked out from the forecast wind.
The progress of the aircraft is monitored carefully, to see if the intended flight path is actually being followed, by spotting a feature on the ground and identifying it on the map, and noting the time that it took to get there.
This gives you a figure for the actual Track Made Good – which may or may not be the same as the Required Track, and a figure for the Ground Speed.
(Speed = Distance to the pinpoint, or Fix, divided by the flight time)

Knowing these two, you can then work out what the Wind velocity actually was, where it differs from that forecast, and using this corrected Wind velocity, you can apply it to the next leg of the journey. This should give you a more accurate arrival at the following turning point. Of course, the wind may not be constant, so the checking procedure should be carried out wherever possible, at all stages of the flight, so that the flight can proceed in a safe and orderly manner, without any undue errors of navigation.

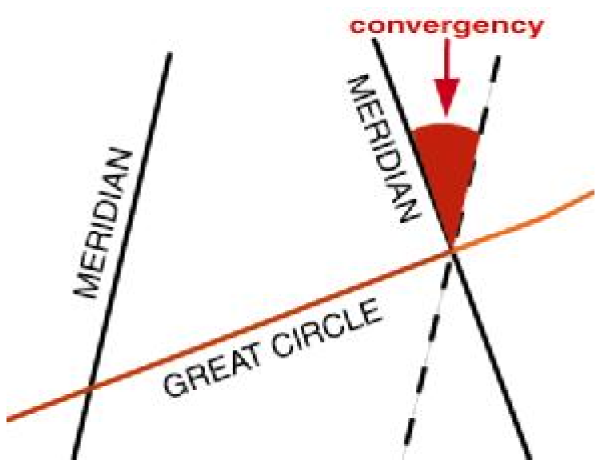
The Virtual E6B computer available as a download from the DC3 Airways site is set up to solve the initial problem at the planning stage (finding Heading and Ground Speed) but so far, I believe, can not give a solution for the Wind Velocity, when you know the other four properties.

4. Great Circles and Rhumb Lines
The World is not flat!

The shortest distance between any two points on the Earth is the route that follows the path of a **Great Circle**. This is a circle with its centre and radius those of the Earth.
The Equator is a Great Circle, and the meridians are each halves of a Great Circle. (The other half is made up of the meridian 180 degrees away from it – its antimeridian.)
Radio waves follow Great Circle paths, as they travel in straight lines, and this should be remembered when taking a bearing from a navigation beacon a very long way away.

All circles drawn on the Earth whose centre and radius are not those of the Earth are **Small Circles**. Examples of these are the parallels of Latitude – apart from the Equator, which is a special case, and mentioned above.

While the shortest route may be along a Great Circle, it is not the easiest to follow, as the direction is constantly changing along the path. This is due to the convergence of the meridians towards the Poles. It is greatest at high latitudes, and decreases to zero at the Equator.
The inclination between any two meridians is called their **Convergency**, and it represents the angular difference between a great circle being measured at either meridian.



(For those of you with scientific calculators,
Convergency = Change of Longitude x Sine of the Mean Latitude)

E.g. For a flight from Gander to Prestwick, the change of longitude is 50 degrees, and the mean latitude is 52 degrees.
Sin 52° equals 0.79
so the convergency is
50 x 0.79 = 39.5
which is very nearly 40 degrees.

In other words, during the flight you would have to continually alter your heading so that by the end of the flight you have changed course by a total of forty degrees.

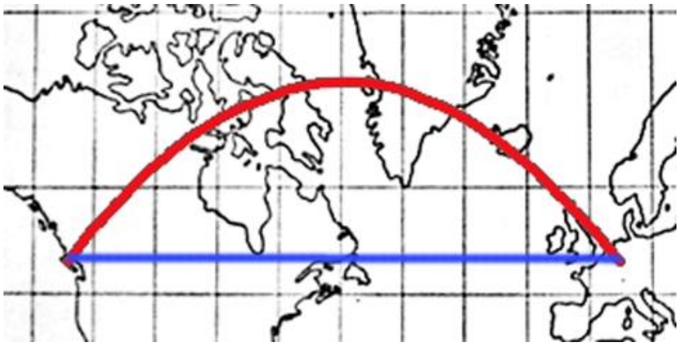
A much easier route to follow is that of the **Rhumb Line**.

This is a curved line that meets successive meridians at the same angle.
It may be a little longer than the Great Circle route, but as it keeps a fixed course all the way, the aircraft can maintain a constant heading.

> *Every rhumb line forms a spiralling path from one pole to the other.*
> *If you travelled in any constant direction other than due East or West,*
> *you would eventually end up at one or other of the poles – fuel permitting.*

On most charts used in aircraft navigation the map projection is such that a straight line on the chart represents part of a Great Circle, and therefore the shortest distance, but on a Mercator projection the meridians are represented by parallel lines, and a straight line on the map would give you a Rhumb Line route.

Great Circle Route (top) and Rhumb Line Route (bottom)
From Vancouver to Paris, seen on a globe.

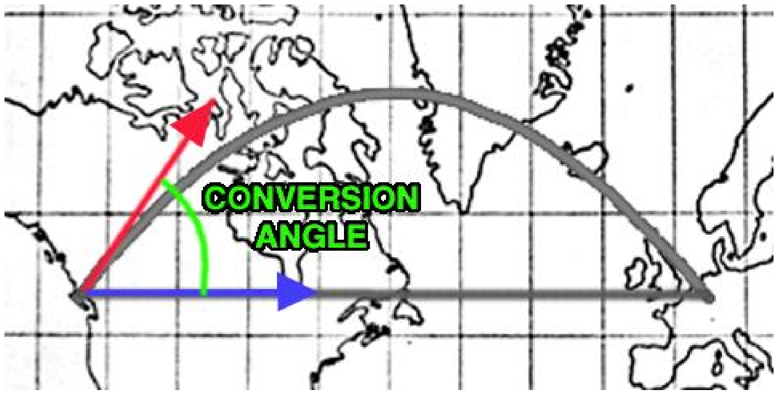


The same route seen on a Mercator chart

The Rhumb Line track follows a constant bearing along the 50 deg. North parallel of latitude, but the Great Circle direction varies from North East to South East along the route.

In all cases in the Northern Hemisphere, the Great Circle route is nearer to the North Pole, and similarly in the Southern Hemisphere nearer to the South Pole.

The only thing we need to know, then, to be able to follow the easier route, would be the direction of the rhumb line that joined the two ends of the portion of the great circle.
This angle between the initial Great circle course, and the Rhumb Line course is called the **Conversion Angle**.

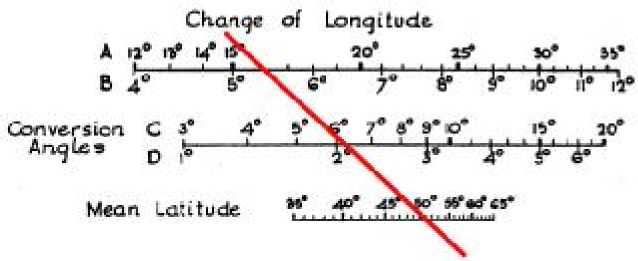


Very simply, **Conversion Angle is half the Convergency**.
(This may not be strictly accurate for very large differences of longitude, or for flights with a mean latitude close to the pole, but it is a very close approximation.)

To follow the much simpler (but a bit longer) Rhumb Line course, all we would have to do would be to work out the Convergency, divide it by two, and add this to the Great Circle course for an easterly heading, or subtract it from the Great Circle course for a westerly heading.

The Great Circle route is always nearer the poles than the Rhumb Line route.

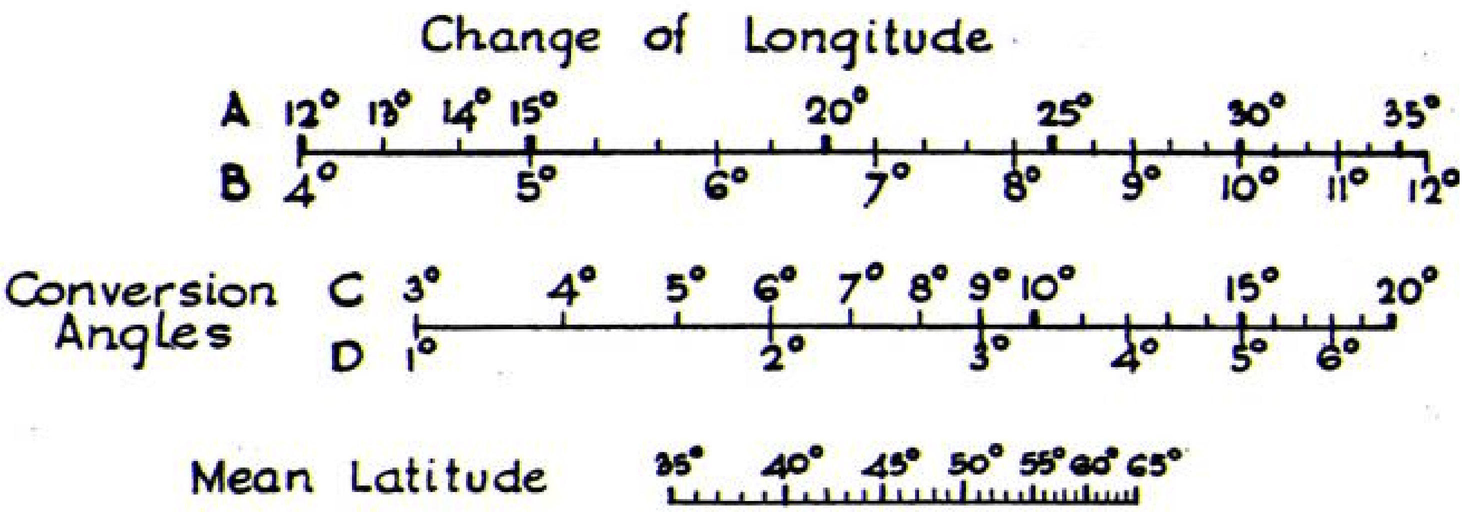
To make life simpler, and to avoid having to do actual calculations, a form of graph has been devised called an "abac".



To use it, first work out the change of longitude between departure and destination, by looking at the map, and also note the mean (or middle) latitude.

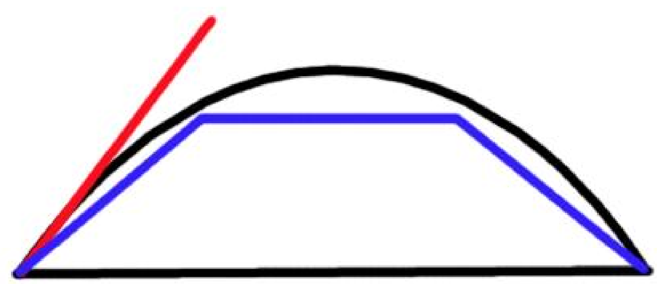
Draw a line from the appropriate figure for the change of longitude on the top scale (either "A" or "B"), to the figure for mean latitude on the bottom scale.
Where the line crosses either "C" or "D" – respectively – gives the figure for Conversion Angle.

In the above example it shows that for two places with a change of longitude of 16° and a mean latitude of 51° the Conversion Angle would be a little over 6°



Blank Conversion Angle abac for flight planning

Rather than go for the shorter, but more difficult to fly Great Circle, or the longer but easier Rhumb Line, what would be done in practice would be to break the long stage into a number of shorter legs, which followed quite closely the route of the Great Circle, but each leg would be of a constant heading – in other words, a rhumb line.
In fact, we only need to break a long Great Circle stage into two or three simple Rhumb Line legs to get a considerable saving in distance, with the benefit of following a constant heading for each leg.



For the division of a long leg into three parts, the courses that are followed for an Easterly heading in the Northern Hemisphere are respectively:

Rhumb Line Course minus two thirds of the conversion angle,
Rhunb Line Course
Rhumb Line Course plus two thirds of the conversion angle.

For the Westerly heading in the Northern Hemisphere, the courses are:

Rhumb Line Course plus two thirds of the conversion angle,
Rhunb Line Course
Rhumb Line Course minus two thirds of the conversion angle.

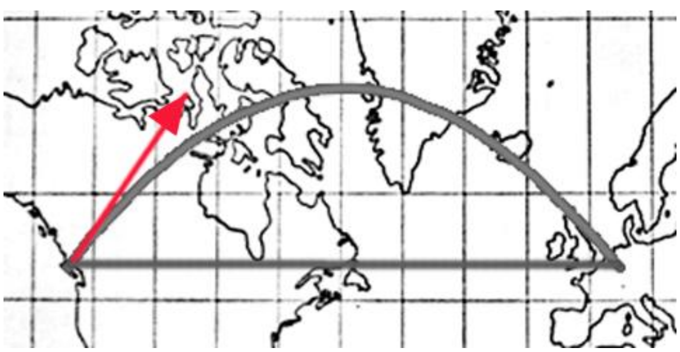
For the Southern Hemisphere, the plusses and minuses are reversed.

5. FS Navigator Great Circle Routes

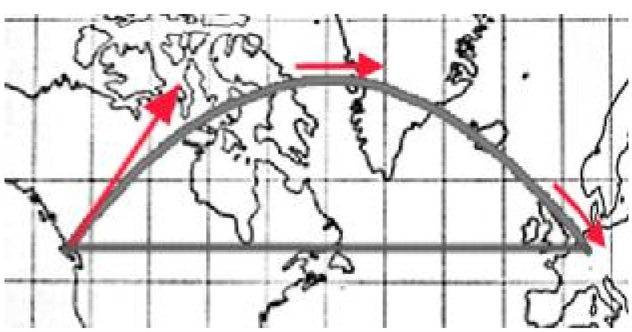
We now come to the important part, as far as route planning is concerned.

FS Navigator, quite correctly, gives Great Circle routes, when being asked for a route from one point to another.
However, the bearing that it gives is only the **initial** course. To follow the route, you would have to be continually changing your heading, to allow for convergency.
This doesn't make any appreciable difference for short routes, but for long routes that cross a number of meridians, if you do not take convergency into account, you could end up tens of degrees off course.

If you didn't alter course, but followed the initial heading given by FS Nav all the way for the Gander to Prestwick example, you would be a VERY long way off course by the time you ran out of fuel. In fact, you would miss Europe altogether, never mind Prestwick!



Initial FS Navigator course for Vancouver to Paris route.



Throughout the Great Circle route, the heading must be changed to keep on course – otherwise you'll end up at the North Pole!

If you feel like checking this, just enter a route from Anchorage, Alaska, to an airport near Oslo, Norway.
The route that it provides has a heading of 16 degrees – not far from due North.
There is no mention of the fact that over the journey the direction changes through East to 170 degrees – almost due South.

If you add a number of extra waypoints all along the route, FS Navigator will show you the bearings for each leg, and you will get to see the true picture. All the different bearings show up, and you will be able to see how the direction changes along the route.
In fact the situation is worse than this, as the track takes you very close to the Magnetic pole, and the bearings vary wildly.

The Rhumb Line track, however, follows the 60 deg. North parallel of latitude all the way, and therefore keeps to a constant heading of 90 degrees – due East.

6. Magnetic North

Be very aware that all the bearings quoted are Magnetic bearings, and that Magnetic Variation varies (of course – as its name implies) over different parts of the globe, and that particularly near to the Magnetic Pole (currently in the general area of the Parry Islands, northwest of Baffin Island) the compass directions will fluctuate wildly.
In real life a magnetic compass would be virtually useless in this area, as there would be very little horizontal strength in the magnetic field, and other methods would be used to work out one's course, for example, an astro-compass.