Theory of Air Navigation

This course deals with the principles of air-navigation, it contains four chapters. The first one introduces definitions, systems and navigation functions. The second chapter explains methods of determining the aircraft position through direction and distance measurements utilizing the electromagnetic waves. The third chapter deals with position determination of aircraft by the inertial methods. The last chapter covers the analysis of navigation errors and the factors affecting the service area.

Chapter_1

الالكترونيات الجوية
Aviation electronics

INTRODUCTION

1.1 Avionics systems and navigation functions :

The aircraft equipment may be divided into four groups :

1- airframe and engine
2- radio - electronics
3- electrical and special instruments
4- armament (for military aircraft)

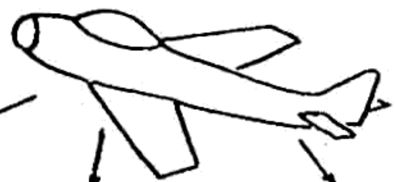
The first group is of the field of mechanical engineering , the others are of the field of electrical specializations. Inspite of this division , the engine - control of modern aircraft contains many of electronic circuits.

Radio-electronic equipment may be divided into five groups , their functions are covered by the following systems :

- airborne radar systems
- navigation systems
- communication systems
- electroptical systems
- electronic - counter - measures (ECM systems)

The word "Avionics" is ; relatively new; short term of the words " Aviation electronics ". It covers many of the aircraft systems, but most of them are systems of radio-electronics as shown in Fig. 1.1.

Aircraft Systems



		Radio-electronics	Electrical & Sp. Instrum.	Armament	Air frame & Engine
Basic systems		- Radars - Navigation - Comm. - Electroptical - ECM.	- Power Sources - Photo eq. - Instruments - Flight control - Data record.	- Guns - Ammunition - Missiles - Sightin & laser Sys.	- Frame - Under-Carrage - Engine - Hydraulic Sys. - Engine Control
Computer applications	special	- Nav. comp. - Fire control comp. - Map reader "	- Image Proc. - Air data Comp. - Flight cont. "	- Weapon data - " control - head up display	
	general	* Automatic Testing and Performance Comp. * Management computer			
Ground electronic sys.		* Simulators * Beacons - Airtraffic control			

—·—·— Avionics systems

Fig. 1.1 Avionics systems

Avionics engineer deals with all kinds of radio-electronic equipment with the necessary information about the other avionics equipment. His duty is to keep all electronic equipment serviceable and improve their combat performance (at the air-bases), to repair the faults of the unserviceable (U.S) equipment at the workshops, and to design new equipment in the field of research.

We are interesting in the navigation systems. Navigation is involved whenever a purposeful change of location takes place. Originally, navigation was almost entirely an art. Man used his senses to determine direction, distance, speed, and position. This was not difficult where landmarks were plentiful; however, when man became bold enough to venture out of sight of land, skill was involved in reading the instruments of nature – the wind, waves, and sky. Although skill is still involved in successful navigation, precise and ingenious instruments have been and are being invented to make the measurements needed in navigation. The successful navigator uses these intelligently and depends on his knowledge to interpret the results and to make decisions regarding future courses of action. Modern technology, then, is applied to play a significant and essential role in navigation, supplementing and enhancing the ability of the human navigator.

a - Definition of navigation

From the foregoing, it can be seen that "navigation is the process of directing the movements of a craft from one

point to another". It involves coordinates of position, direction, time, and speed. The craft may be any vehicle capable of purposeful motion.

The navigation necessary to successful completion of any flight may be performed by a specialist navigator, the pilot or copilot, or someone on the ground who either coaches the pilot by means of ground equipment (e.g. radar) and communications or else programs a black-box to provide the necessary outputs to control the aircraft.

The various radio facilities, lights, instruments, and the like used in the navigation of the craft are called navigational aids. These take many forms and numerous techniques are employed in their use. From the available aids, the prudent navigator selects those that are appropriate to the situation, attempting always to maintain some form of complementary redundancy to provide a check and backup in case of failure of the primary method. When human lives are involved, too much depends on successful navigation to rely entirely on one sensor.

b- Purpose of navigation

Traditionally, navigation of slow-moving craft has been involved primarily in answering the question, "Where am I?". From the answer the captain then decided whether to continue the present heading and speed or to make some alternation.

As speed increased and number of aircraft multiplied, the time lag between measurement and decision regarding

the significance of positional information became over more intolerable. The aircraft navigator began to ask, "Which way, and how far?" to the destination or next waypoint. As the number of aircraft continues to increase, limiting the amount of airspace available to individual aircraft, an additional question becomes increasingly important: "Where am I with respect to where I should be at this moment?". Accordingly, continuous, real-time outputs of steering information and coupling of the autopilot directly to a guidance computer are becoming more common.

1.2. Craft and environment

1.2.1. Craft

Navigation has been defined as the business of conducting a craft as it moves about its ways. Satellites in fixed orbits, missiles that are aimed and not steered, and vehicles that travel on rails, are unable to move about their ways and cannot be navigated. In general, craft that are navigated may be classified according to the medium on which they operate. This gives four classes:

a- Land vehicles:

They may travel on wheels, tracks or skids. Navigation applies to operations over untracked country such as deserts or arctic wastes

b- Marine vessels: These include:

i- Power-driven surface craft which may be large

ships or small boats.

ii- sailing craft

iii- submarines

iv- under water missiles

c- Aircraft :

Discounting ballons and airships, the main categories will be :

i- Aeroplanes : supported by aerodynamic lift, generally from wings and power driven. The aeroplanes are either propeller driven of speed up to 400 knots (knot = 1 nautical mile / hour) or jet of speed up to 2000 knots or more.

ii- Gliders : supported by wings but not powered, with speed upto 60 knots or more.

iii- VTOL : vertical take-off and landing or V/STOL (vertical and short take-off and landing) includes rotating-wings craft such as helicopters.

iv- Missiles : that operate in the air. These are either offensive missiles lunched from the ground (SSM, surface-to-surface missiles) or from the air (ASM, air-to-surface missiles), or defensive missiles launched from the ground (SAM, surface-to-air missiles) or from the air (AAM, air-to-air missiles)

d- Space craft :

Initial lift-off is by launchers similar to those used for launching long-range ballistic missiles. The main classes will be :

i- Navigational sattelites which follow fixed orbits
ii- Controlled satellites of which the orbits can be varied
iii- Space craft that operate in areas where the earth gravitational field does not predominate

1.2.2. Environment

We discuss the atmosphere in which the aircraft operate and give some information about the world winds, visibility, ice and the forecasting.

a- The World :

1- The universe :

The universe includes a number of galaxies each composed of millions of stars. The stars, even within a galaxy, are extremely remote from each other. The Sun is a typical star in a galaxy with a near neighbour about 25 million million miles away.

Around the Sun, a number of planets travel in elliptical orbits generally close to the plane of the earth's orbit, which is known as the plane of the ecliptic. The earth which is one of the planets close to the Sun, travels in orbit at an average distance from the Sun of 93 million miles. The earth rotates on its axis at an angle to the ecliptic of about 66 1/2°. The earth rotates on its axis once every 23 hours, 56 minutes and 4 seconds. The Moon travels round the earth once a month and rotates once a month so that

the same face is always seen.

2- The time :

The mean time at which the Sun passes overhead at Greenwich is calculated, and this time is taken to be midday Greenwich Mean Time, generally written 1200 GMT. GMT is the standard time for navigation, and navigators use a 24-hour clock. Time-keeping accuracies are of the following orders :

a - Mechanical watch or chronometer, a second per day.

b - Crystal controlled clock, a second in months.

c - Atomic clock, a second in centuries.

3- Rotation of the earth :

At the equator, the surface is tilting at 360° a day or 15° an hour, but it is not rotating. At the poles, the surface is rotating at 15° an hour, but it is not tilting. For other places, the earth rotatation causes:

- tilt at 15° cos (latitude) / hour
- rotation at 15° sin (latitude) / hour
- coriolis acceleration in moving craft which distorts the direction of gravity by 0.0004 x speed in knots x sin (latitude) degrees.

4- Structure of the earth and atmosphere :

Three-quarters of the surface of the earth is covered by water, most of which has a salt content of 3-4%. The surface has mountains upto 5 miles high and ocean deeps more than 6 miles deep. The average depth of

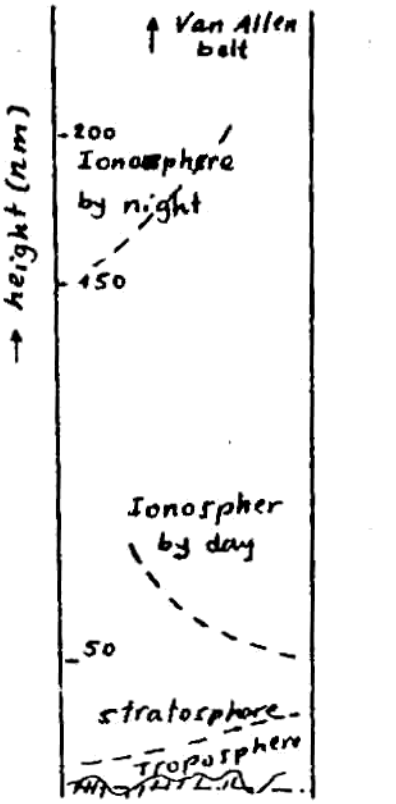
the sea is over 10,000 feet, whereas the average height of the land is less than 2500 feet.

Air is composed of a mixture of gases, about 3/4 being nitrogen and a litle over 1/5 being oxygen. As the surface of the earth is left, the air becomes gradually less dense. Half the atmosphere is concentrated below 20,000 feet, and almost all the rest below 10 miles.

Water vapour is concentrated in the lower levels of the atmosphere, known as the troposphere. The upper limit of the troposphere is known as the tropopause. Above the tropopause the atmosphere is known as the stratosphere.

At heights of about 30 - 40 miles by day, rising to about 200 miles at night, layers of electrically charged particles are found in the rarified air. These layers stretch upwords several hundered miles, the whole forming the ionosphere. Further out, at distance of between 5,000 and 15,000 miles, are layers of radiating particles known as the Van Allen belt. See Fig. 1.2.

The way in which the density and temperature of the air changes with height above sea-level will vary from place to place and from time-to-time. The graph in Fig. 1.3. shows the standard atmosphere reasonably close to the overall average which has been agreed by the International Civil Aviation Organization (ICAO). It is assumed that the sea-leval pressure is 1013 millibars at a temperature of 15°C.



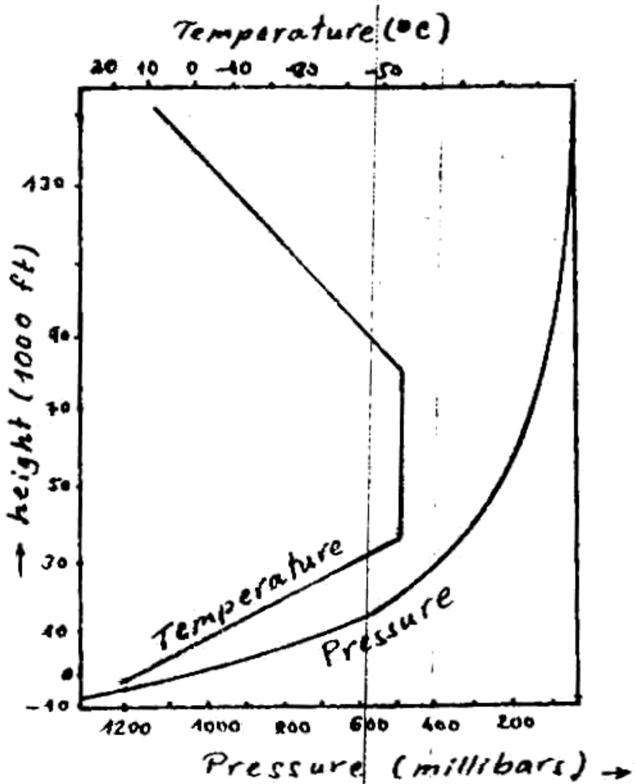


Fig. 1.2. The atmosphere

Fig. 1.3. ICAO standard atmosphere

b- The weather :

The navigation of a craft on or above the surface of the earth is affected by the weather, mainly in one of three ways :

- Vertical air currents and the resulting winds may affect progress directly by wind pressure or indirectly, for example, by the waves at sea.
- Poor visibility at the surface of the earth can hamper navigation, particularly terminal navigation.
- Ice can form on the craft or on the land or on the sea.

C- Forecasting :

The accuracy of the meteorological forecast depends on whether there is ample meteorological information available not only in the area but also in the adjacent area from which the weather comes. The information at height is frequently incomplete, but fortunately, the weather at height is generally less unpredictable.

The forecaster may also be aided by prognostic charts based upon how weather situations have developed in the past. The way that the weather develops is generally more predictable in tropical regions than in temperate regions. Although the forecaster may be able to predict what the weather will be, it may be even more difficult to judge where it will be.

It is doubtful whether the navigation of any craft except possibly a very high-flying aircraft can avoid taking account of the weather forecast. Even in this case, weather will affect the terminal phase of the journey. Although the aircraft itself may be able to land, fog, ice, and strong winds may disrupt the surface transport to an extent that there is no arriving of the aircraft.

الشكل الهندسي للارض

1.3. Geometry of the earth and Coordinate frames

1.3.1. Geometry of the earth

The earth is a spheroid ; that is ; it is roughly spherical in shape. There are a number of departures from a perfect sphere due to both irregularities in the earth's surface and the fact that the earth's rotation causes a bulge at the equator. The earth's shape and size, rate of rotation and mass attraction are all measurable characteristics of importance in the operation of navigation systems.

The Newtonian gravitational attraction of the earth is represented by gravitational field G. Because of the rotation of the earth, the apparent gravity field g is the vector sum of the gravitional and centrifugal fields. (Fig. 1.4)

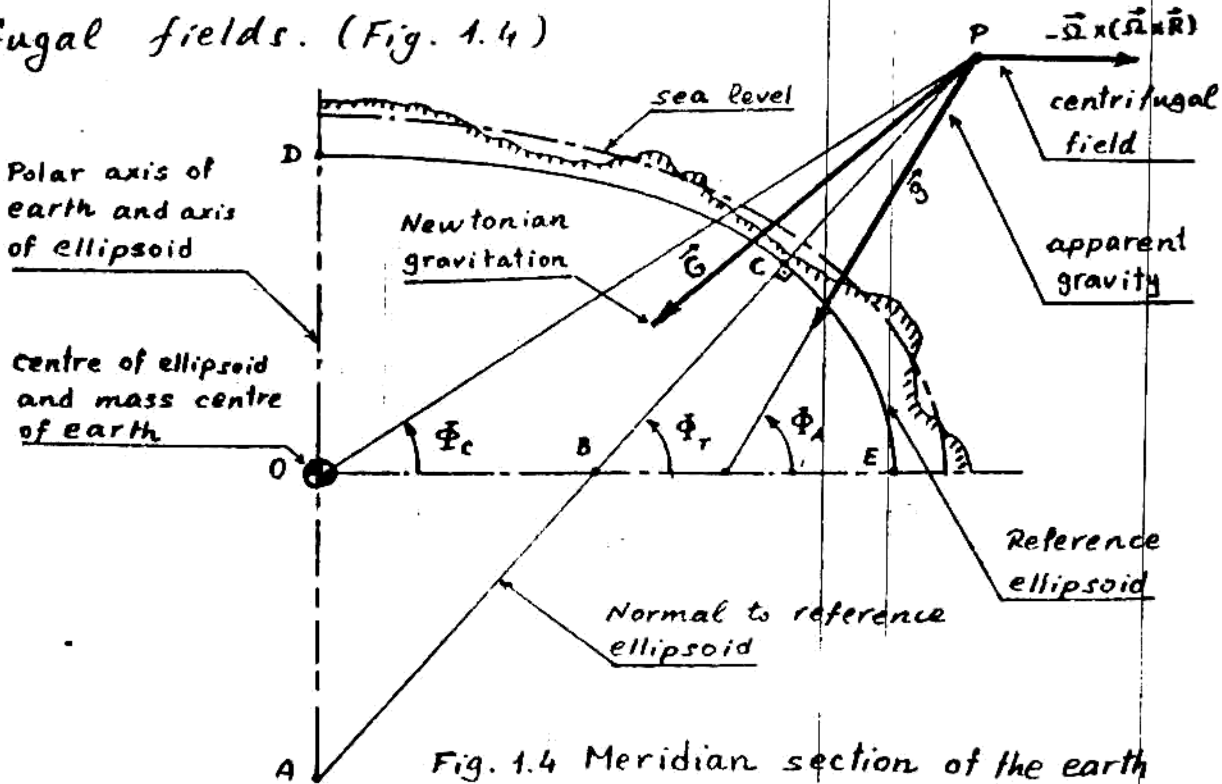


Fig. 1.4 Meridian section of the earth showing the reference ellipsoid and gravity field

From the Fig. 1.4, the following are:

Φ_A = astronomic latitude of P , PC = h = height above ref. ellip.

Φ_T = geodetic " " " , OE = a = semimajor axis

Φ_C = geocentric " " " , OD = b = semiminor "

and

$$\vec{g} = \vec{G} - \vec{\Omega} \times (\vec{\Omega} \times \vec{R}) \qquad (1.1)$$

where Ω is the inertial angular velocity of the earth (15.04107 deg./hr) and R is the radius vector from the mass centre of the earth to a point P where the field is to be computed. The direction $\vec{g}$ is the "plumb bob", or "astronomic" vertical

In cooling from a molten mass the earth has assumed a sphere whose surface is a gravity equipotential and is nearly perpendicular to $\vec{g}$ everywhere (i.e. no horizontal stresses exist at the surface). For navigational purposes, the earth's surface can be represented by an ellipsoid of rotation around the earth's spin axis. The size and shape of the best-fitting ellipsoid are chosen to best represent the sea-level equipotential surface.

Mathematically, the centre of the ellipsoid is at the mass centre of the earth; and the ellipsoid is chosen so that to minimize the mean-square deviation between the direction of gravity and the normal to the ellipsoid, when integrated over the entire surface. National ellipsoids have chosen to represent the earth in localized areas, but they are not always good worldwide approximations. The centres of these national ellipsoids are not exactly coincident and do not

exactly coincide with the mass centre of the earth. The navigator does not ask that the earth be mapped onto the optimum ellipsoid. Any ellipsoid is satisfactory for world-wide navigation if all points on the earth are mapped onto it.

The geometry of the ellipsoid is defined by a meridian section whose semimajor axis is the equatorial radius a and whose semiminor axis is the polar radius b as shown in Fig. 1.4. The accentricity of the elliptic section is defined as $\varepsilon = \sqrt{a^2 - b^2}/a$, and the ellipticity, or flattering as $f = (a-b)/a$.

The radius vector R makes an angle Φ_c with the equitorial plane, where Φ_c is the geocentric latitude; R and Φ_c are not directly measurable. The geodetic latitude Φ_T of a point is the angle between the normal to the reference ellipsoid and the equitorial plane. Geodetic latitude is our usual understanding of map latitude. The term "Geographic latitude" is sometimes used synonymously with "geodetic".

The radius of curvature of the ellipsoid are of fundamental importance. The radius of curvature is a function of position and heading due to its departure from a spherical shape. The change is sufficiently great that account must be taken of it when navigational accuracies of the order of 20 miles or better are desired.

For numerical work :

$$a = 6378.163 \ km$$

$$f = 1/298.2 = 3.353454 \cdot 10^{-3}$$

$$\varepsilon = f(2-f) = 6.6956624 \cdot 10^{-3}$$

$$b = a\sqrt{1-\varepsilon^2} = 6378.020028 \ km$$

average $R \doteq 6371.110$ km.

$$g = 978.0491(1 + 0.00529 \sin^2 \Phi_T) \ cm/s^2$$

within $0.02 \ cm/s^2$. It decreases $10^{-6} g$ for each 10-ft increase in altitude above the sea level. This decrease of acceleration is due to the decrease of mass-attraction of the earth for increase of altitude (inverse square law of attraction applied), the earth has a mass of approximately 6.6×10^{21} tons.

1.3.2. Coordinate Frames

The basic coordinate frame for earth-navigation is shown in Fig. 1.5. as y_i rectangular coordinates whose origin is at the mass centre of the earth, whose y_3 axis lies along the earth's spin axis, and which rotates with the earth.

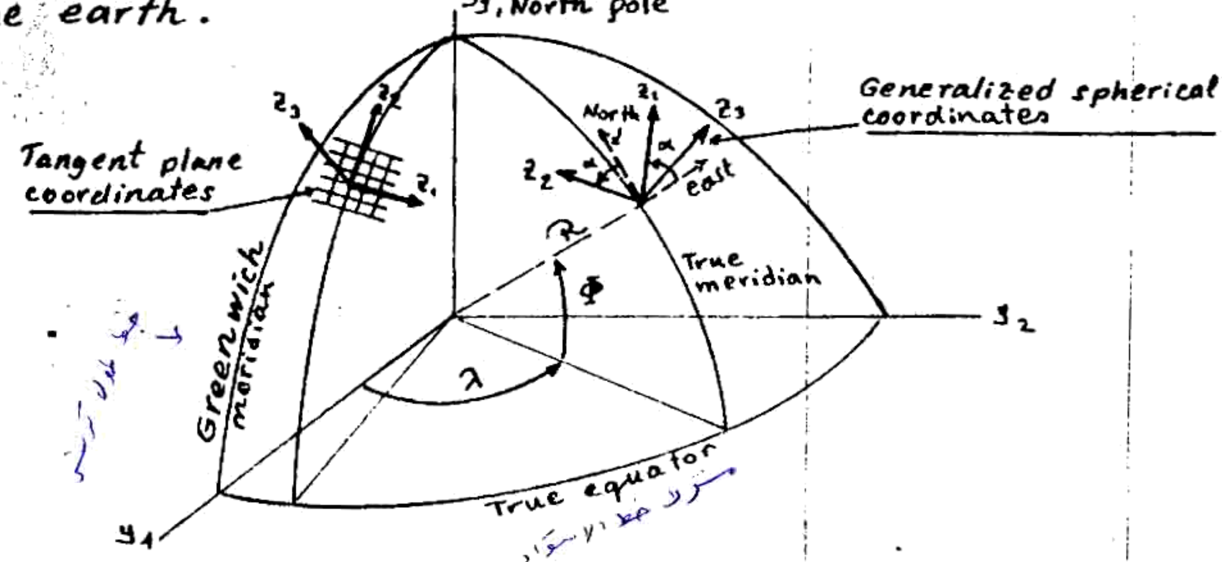


Fig. 1.5. Navigation coordinate frames

The rectangular coordinates y_1, y_2, y_3 are inconvenient for specifying the location of aircraft operating near the earth. A large number of more convenient orthogonal coordinates, called z_i, can be introduced. Some of the more common are the following:

1- Geocentric spherical coordinates (λ, Φ_c, R):

These are the spherical coordinates of the radius vector $\vec{R}$. The symbol z_1 represents longitude λ; z_2 is the geocentric latitue Φ_c; and z_3 is the radius. The geocentric latitude requires knowledge of the direction toward the mass centre of the earth, a direction that is not directly observable. (Fig 1.6)

2- Geodetic spherical coordinates (λ, Φ_T, h):

These are the spherical coordinates of the normal to the reference ellipsoid (Fig. 1.7). The symbol z_1 represents longitude λ; z_2 is the geodetic latitude Φ_T; and z_3 is altitude h above the reference ellipsoid. Geodetic coordinates are commonly used on maps and navigation systems.

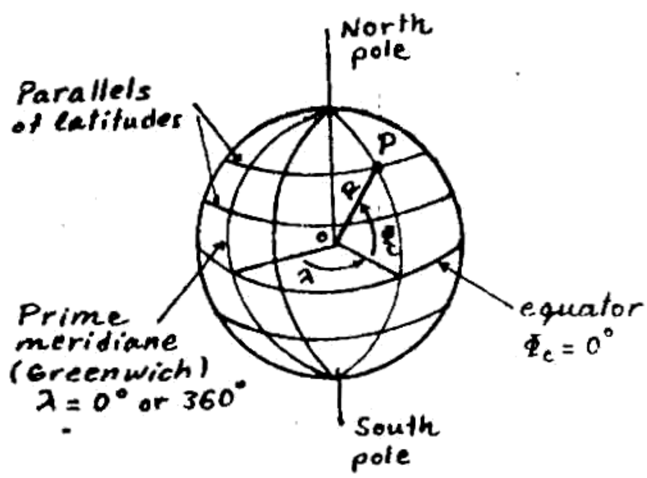


Fig. 1.6- Geocentric spherical coordinates (λ, Φ_c, R)

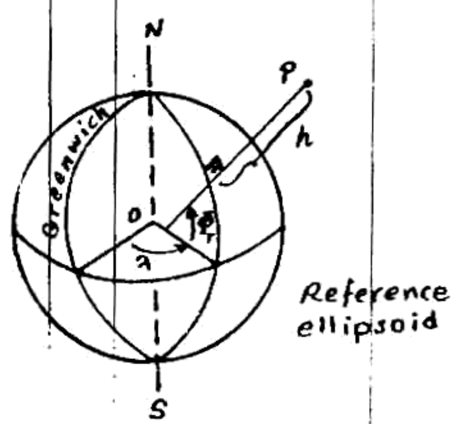


Fig. 1.7. Geodetic spherical coordinates (λ, Φ_T, h)

3- Generalized spherical coordinates (9 direction cosines)

These coordinates are the nine direction cosines (C_{ij}) of a locally level set of z_i (with arbitrary azimuth) relative to the y_i. They are convenient for world-wide navigation because they exhibit no singularities. Physically understandable coordinates such as latitude-longitude must be derived from the C_{ij}.

Many problems require transformations between two sets of orthogonal three dimensional coordinate systems. The mathematics of the coordinate transformations is illustrated by the relationships between the generalized direction cosines C_{ij} and the latitude Φ, longitude λ, and wander angle α. This angular transformation is illustrated in Fig.1.8.

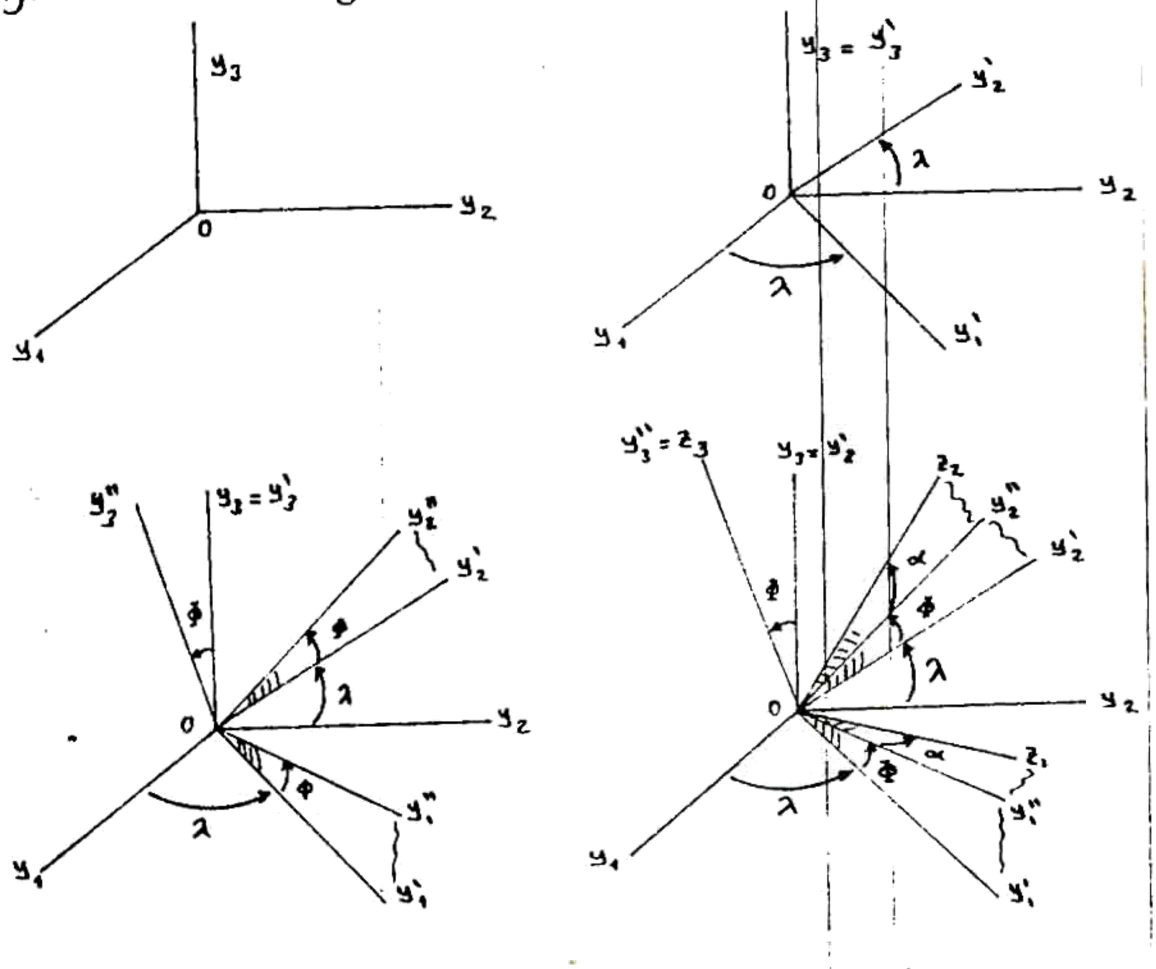


Fig. 1.8. Angular Transformation

The rectangular coordinates (y_1, y_2, y_3) are rotated through an angle λ in the $y_1 y_2$ plane, this rotation generates the coordinates (y'_1, y'_2, y'_3). These new coordinates are rotated by an angle Φ in the $y'_1 y'_3$ plane and the result is the coordinates (y''_1, y''_2, y''_3). These new one are also rotated by an angle α (The wander angle) in the $y''_1 y''_2$ plane. The result is the z coordinates (z_1, z_2, z_3).

The mathematics of the coordinate tranformation is illustrated by the relationships between the generalized direction cosines C_{ij} and the latitude Φ, longitude λ, and the wander angle α. Any vector V can be resolved into the y or z coordinat frame. The y and z component of V are related by the equation

$$[V]_z = [C][V]_y \qquad (1.2)$$

where [C] is the transformation matrix with the elements $\{C_{ij}\}$. The navigation-computer calculates in terms of the $\{C_{ij}\}$ which are usable everywhere on earth. The familiar geographic coordinates can be found in terms of $\{C_{ij}\}$. In polar regions the navigation systems operate on the basis of the $\{C_{ij}\}$

4- Transverse - Pole spherical coordinates :

These coordinates are analogous to geocentric spherical coordinates except that their poles are deliberately displaced from the geographic north and south poles.

The symbol z_1 represents the transverse longitude ; z_2, the transverse latitude ; and z_3 , the radius . These are used to permit nonsingular operation near the north or south poles, by placing the transverse pole on the true equator. Transverse polar coordinates are much simpler than generalized spherical coordinates since they involve only three z_i variables instead of nine direction cosines. However they do not eliminate the singularity ; they merely move it to some location at which flight operations are not expected. These coordinates are particularly useful for the analog mechanization of short-range systems. (Fig. 1.9).

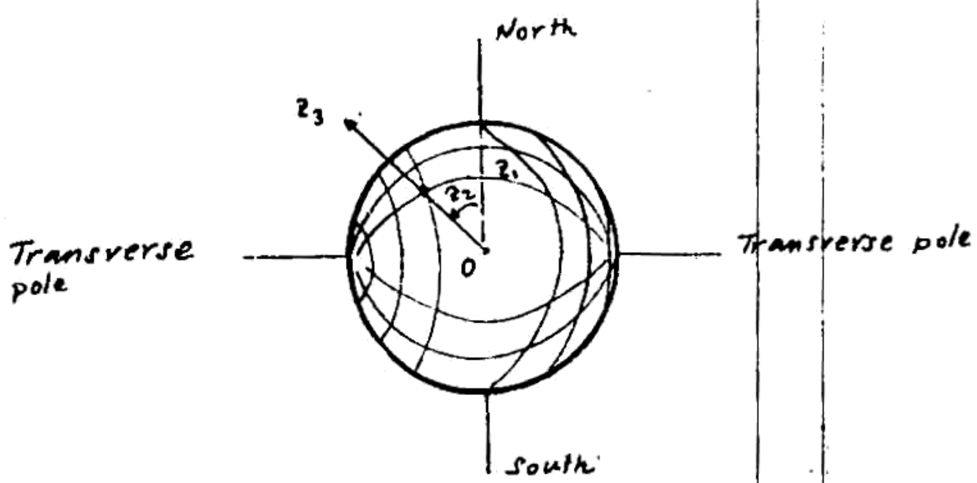


Fig. 1.9 Transverse-pole spherical coordinates

5- Tangent plane coordinates :

These coordinates are always parallel to the locally level axes at some destination point (Fig. 1.5). They are locally level only at that point and are useful for flight operations within a few hundered miles of a single

destination, as shown in Fig. 1.5, z_3 lies normal to the tangent plane, and z_2 lies parallel to the meridian through the origin, it indicates the local north, while z_1 indicates the local east direction.

6- Tangent cylinder coordinates :

The z_i are the radius, down-range angle, and lateral departure of the aircraft from the great circle along which the cylinder is tangent to the sphere. as shown in Fig. 1.10.

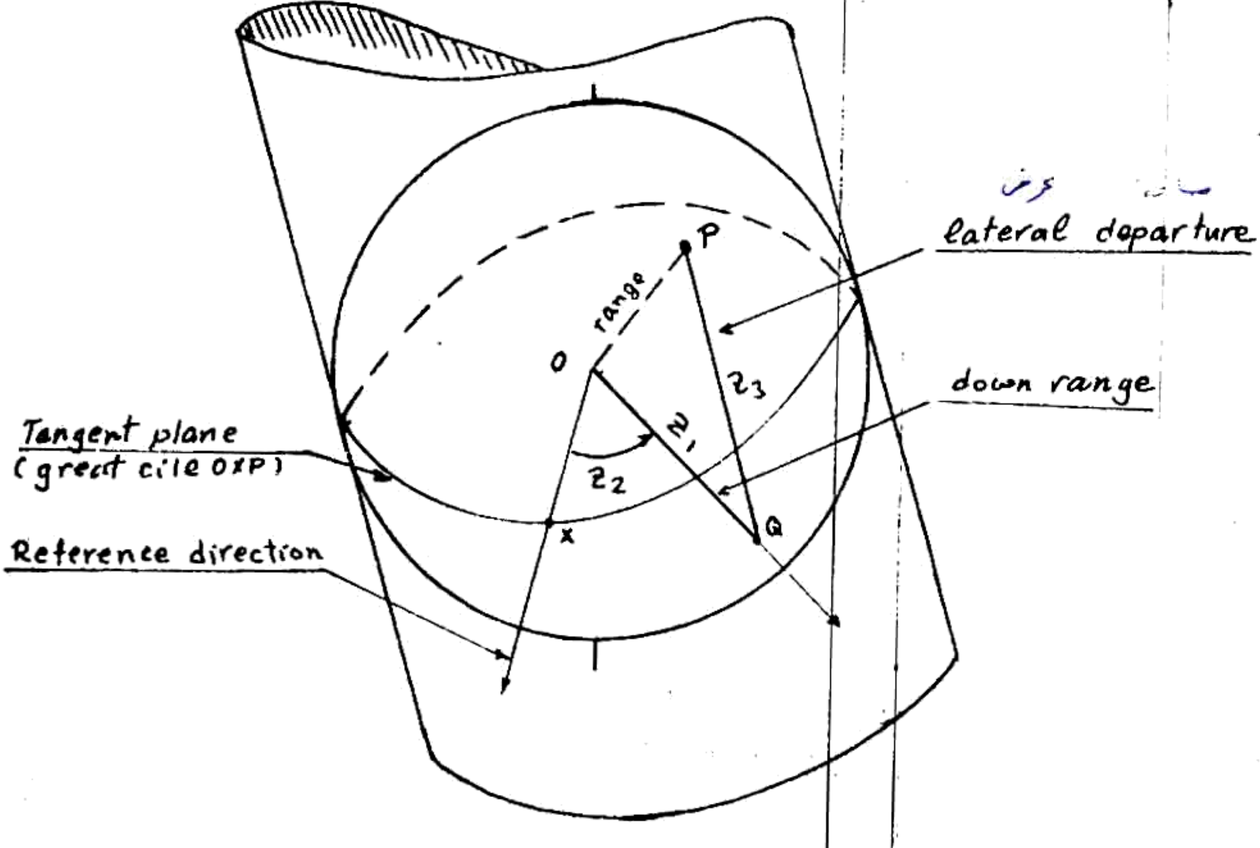


Fig. 1.10. Tangent cylinder coordinates

Tangent cylinder coordinates are useful for aircraft fly on nearly great-circle routes. They are similar to transverse polar coordinates near the cicle of tangency (the transverse equator)

7- Map-grid coordinates :

The navigation computer can calculate position in

map-grid coordinates such as Lambert conformal or transverse Mercator xy coordinates. These are not convenient for long-range navigation.

The coordinate frames discussed above have a unique orientation at every point in the vicinity of the earth. Other coordinate frames do not have this property.

1.4. Navigation Quantities

1.4.1. Attiude and heading

- Aircraft rotations

An aircraft is equiped with certain fixed and movable surfaces, or airfoils, which provide for stability and control during flight. These are illustrated by Fig. 1.11.

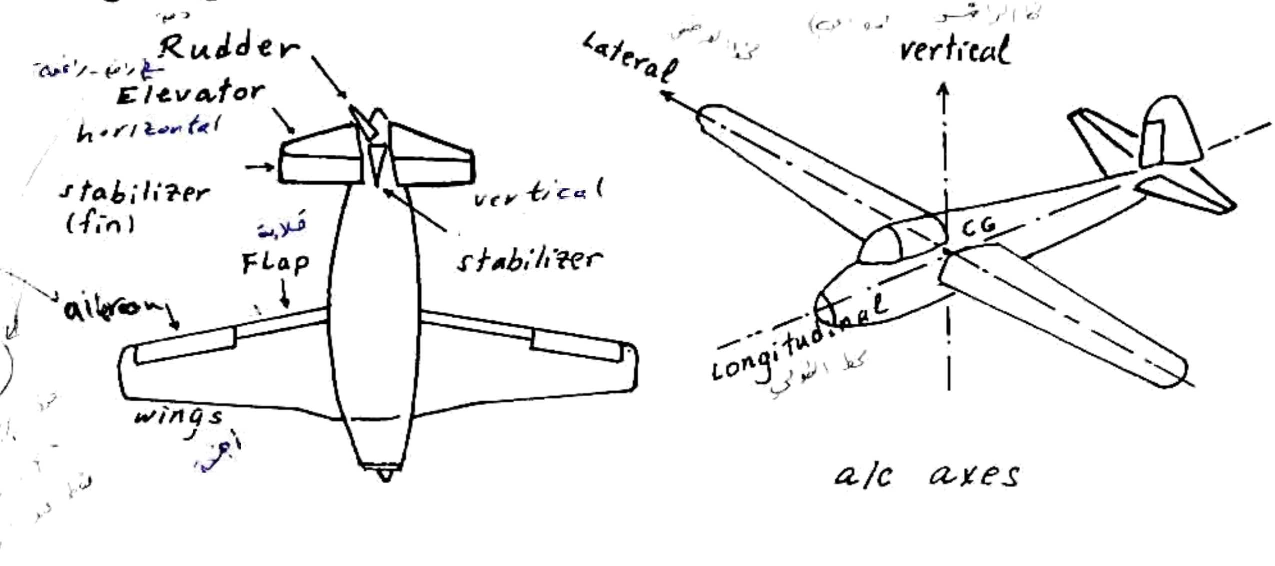


Fig. 1.11 Aircraft-control-surfaces

Each of the named airfoils is designed to performe a specific function in the aircraft-flight. The fixed foils are the wings, the vertical stabilizer (fin), and the horizontal stabilizer. The movable airfoils, called control surfaces, are the airelons, elevators, rudder, and flaps. The airelons, elevators and rudder are used to "steer" the aircraft in flight to make it go where the pilot wishes to go and to cause it to execute certain maneuvers. The flaps are normally used only during landings and sometimes for take-off. Large jet aircraft, gliders and some other types of aircraft are equiped with lift-control devices

called spoilers. These are rectangular surfaces mounted on top of the wing. When it is desired to reduce the lift of the wing, the spoilers are raised into the air stream.

An aircraft has three axes of rotation, namely the longitudinal axis, the vertical axis, and the lateral axis. It is important to note that all three axis pass through the centre of gravity of the aircraft (CG). This is why the CG must be located within certain limits if the aircraft is to fly satisfactorily.

-Aircraft Roll (Aileron - effect):

An aileron may be defined as a movable control surface attached to the trailing edge of a wing to control an aircraft in "roll", that is, rotation about the longitudinal axis. The conventional aircraft has two ailerons, one attached to each wing. They are riggid so that when one is applying an upward force to one wing, the other is applying a downword force to the opposite wing, as shown in Fig. 1.12.

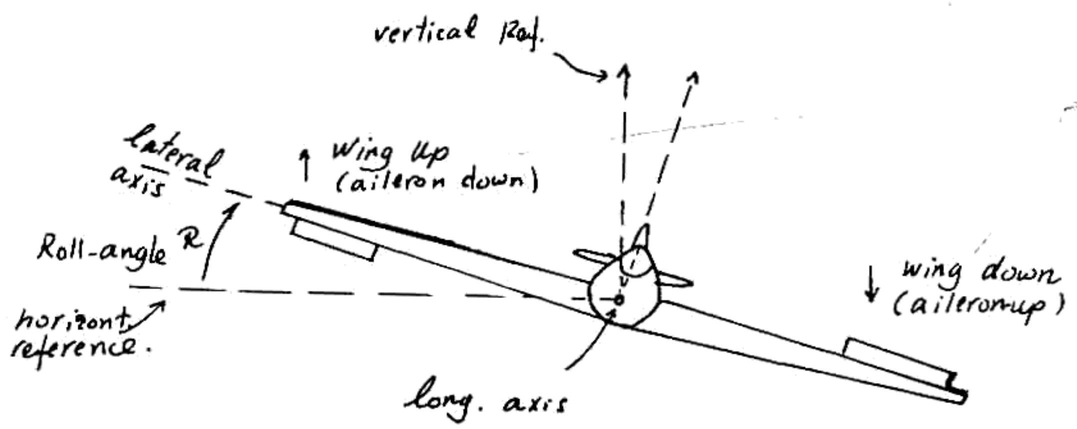


Fig. 1.12 Roll of aircraft (aileron-effect)

The ailerons are moved by means of a control-stick or wheel in the cockpit. During normal turns of an aircraft, the movement of ailerons is coordinated with the movements of the rudder and elevators to provide a banked horizontal turn without "slip" or "skid".

- Aircraft - Pitch (Elevator-effect)

An elevator is defined as a horizontal, hinged control surface usually attached to trailling edge of the ~~horizontal~~ stabilizer of an aircraft, designed to apply a Pitching moment to the aircraft. A pitching moment is a force tending to rotate the aircraft about the lateral axis, that is, "nose up" or "nose down" as shown in Fig. 1.13

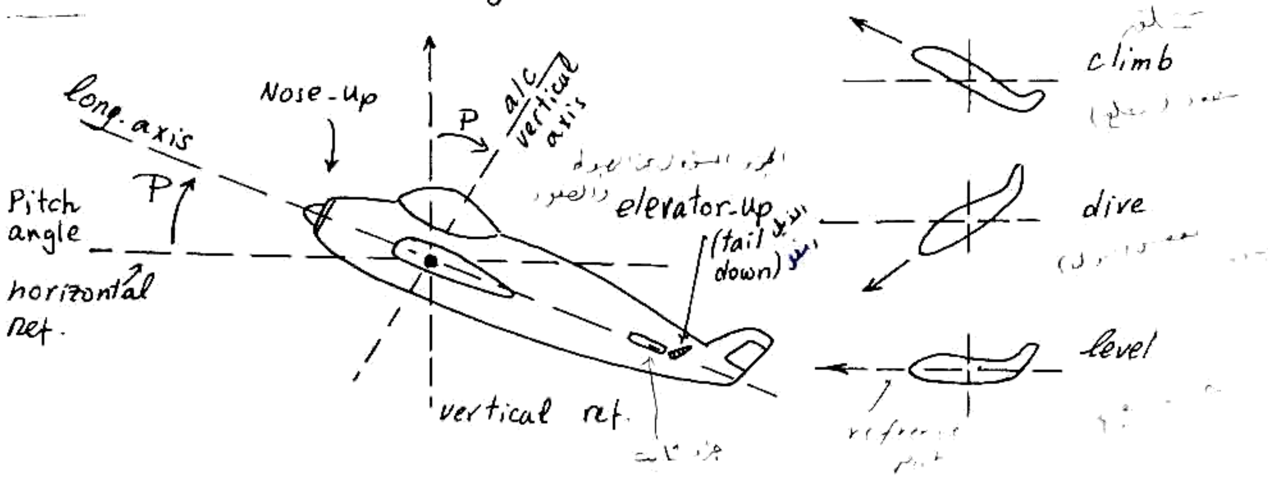


Fig. 1.13. A/c Pitch (elevator-effect)

When the control stick is pulled back, the elevators are raised. The force of the relative wind on the elevator surfaces tends to press the tail down, thus causing the nose to pitch up, and the angle of attack of the wings to increase

- Aircraft Yaw ("Turn", the rudder-effect)

A rudder is a vertical control surface usually hinged to the tail unit aft of the vertical stabilizer and designed to apply

Yawing moment to the aircraft, that is, to make it turn to the right or left about the vertical axis, as shown in Fig. 1.14.

The movement of the rudder is controlled by pedals or a "rudder bar" operated by the feet of the pilot. When the right pedal is pressed, the rudder swings to the right, thus bringing an increase of dynamic air pressure on its right side. This increased pressure causes the tail to swing to the left and the nose to turn to the right.

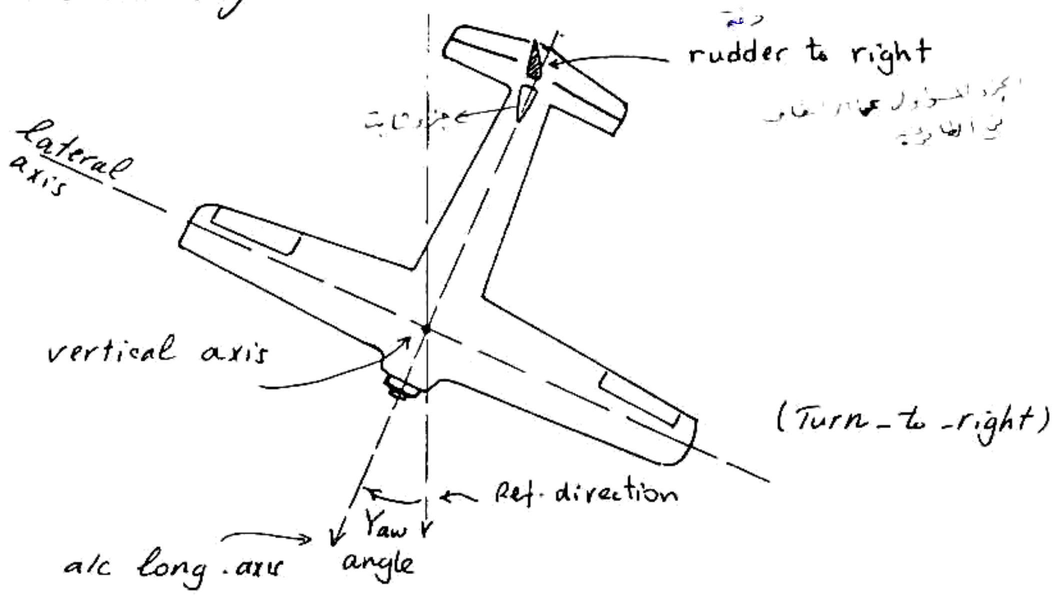


Fig. 1.14. A/C Yaw (turn) (rudder-effect)

Although it appears that the rudder causes the aircraft to turn, it must be pointed out that the rudder itself cannot cause the aircraft to make a good turn. A properly executed turn requires the use of all three of the primary controls in order to prevent skid and slipping.

Aicraft attitude and heading references:

A/C attitude is a state-indication of its pitch and roll. These indications need vertical and horizontal references. In

the simplest case, the attitude reference may be the vissible horizon. All practical attitude references except magnetic compasses require gyroscopes (chapter.3), A special instrument known as " attitude-indicator" or " Flight-director " is shown in Fig. 1.15.

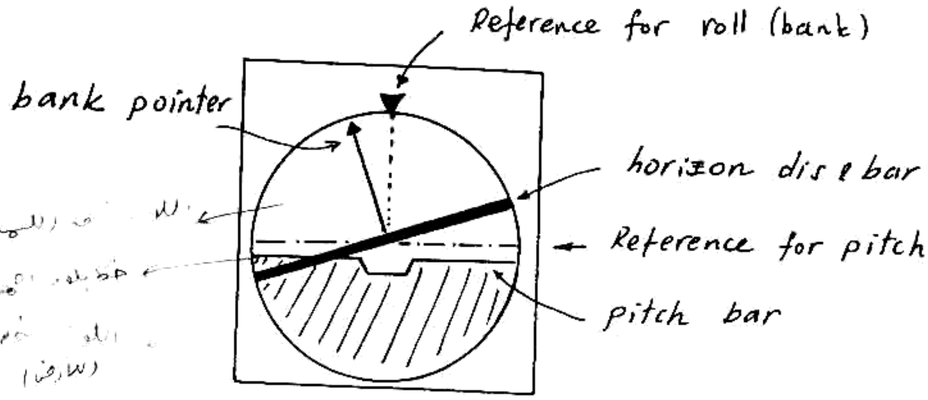


Fig. 1.15. A/C attitude-indicator (Flight-director)

The a/c heading or course is the alignment of the longitudinal axis in the plane parallel to the earth-surface, known as the horizontal plane (or azimuth plane). The longitudinal axis alignment is taken with respect to a reference direction, as shown in Fig. 1.16.

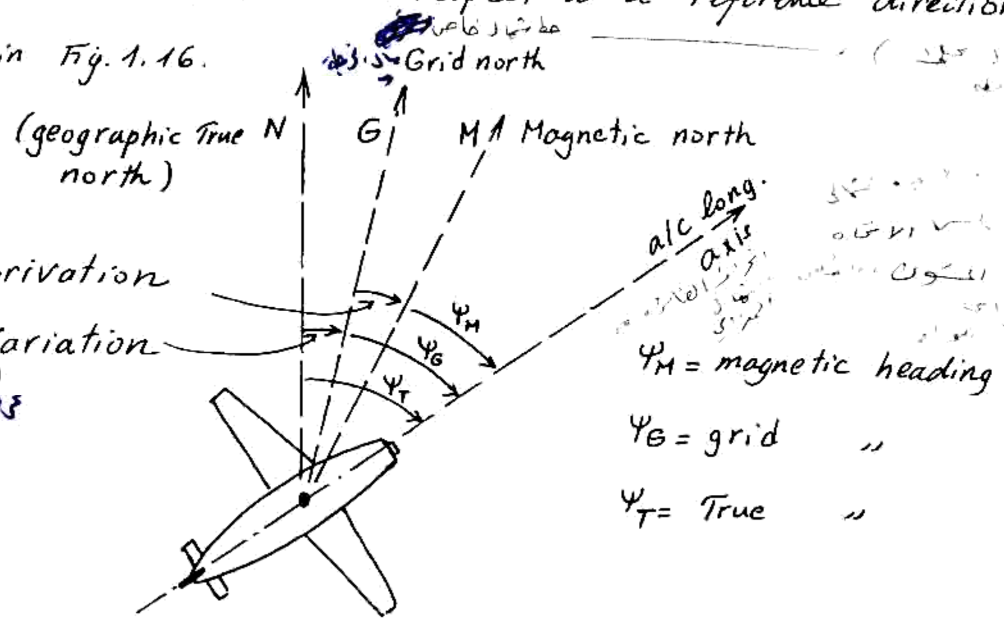


Fig. 1.16. A/C heading

The heading references are :

a. True (T), with reference to meridian (Ψ_T)

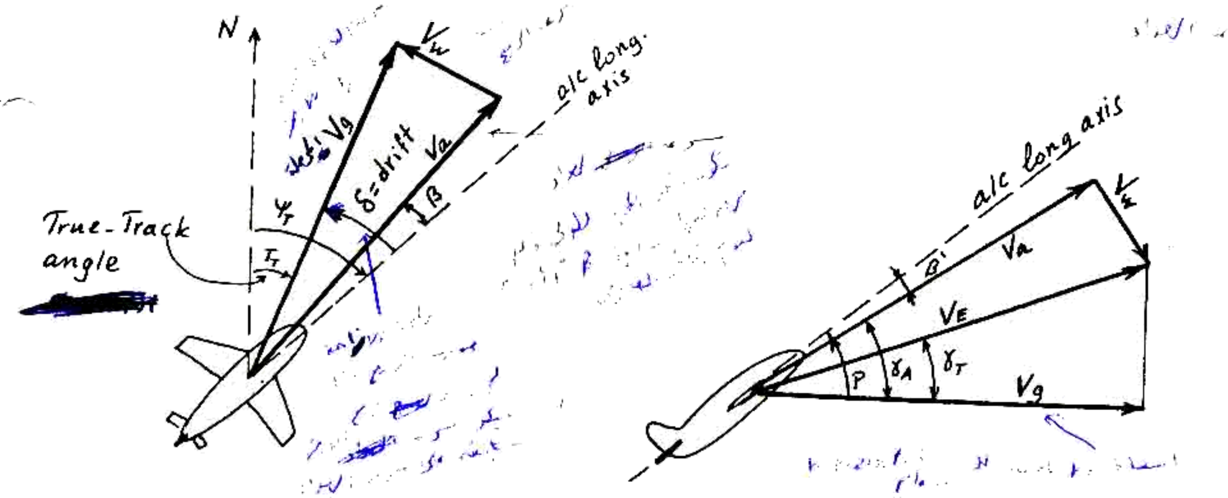
b. Magnetic (M) " " " magnetic meridian (Ψ_M)

c. Grid (G) " " " great circles or arbitrary axis

1.4.2. The Speed-Triangle مثلث السرعة

Velocity has two elements, direction of motion and speed of motion. Velocity is always measured according to some frame of refrence which may be the earth-surface, a moving object in space, or the craft.

The velocity of a craft compared to the earth-surface is known as the ground velocity. The speed is known as the ground speed and the direction as the track-angle or the course. Like heading, course is measured by a three figure number (indicating angles from 000° to 360°) and suffixed T, M, or G according to whether it is measured in true, magnetic or grid directions. see Fig. 1.17.



V_w --- wind speed vector
V_a --- air " "
V_g --- ground " "
δ --- drift angle

V_E --- earth speed vector
γ_A --- air-mass flight path angle
γ_T --- earth-ref. " " "
β, β' --- sideslip angles

Fig. 1.17. Speed Triangle

A/C can measure its heading and its speed through the air. The velocity of the a/c through the air, when combined with the wind velocity will give the ground velocity.

β and β' are known as the side-slip angles, they are due to unbalance of aerodynamics of the a/c. They are of order 1°-2° and usually neglected in navigation calculation, it means, we consider that the air-speed is directed along the longitudinal axis of the aircraft.

The drift angle is the angle between the air-speed and the ground-speed. It is measured from the air-speed vector to the ground-speed vector and suffixed L or R (left or right).

The wind direction in the horizontal plane is measured from the north-reference direction (from 000° - 360°) in clockwise direction.

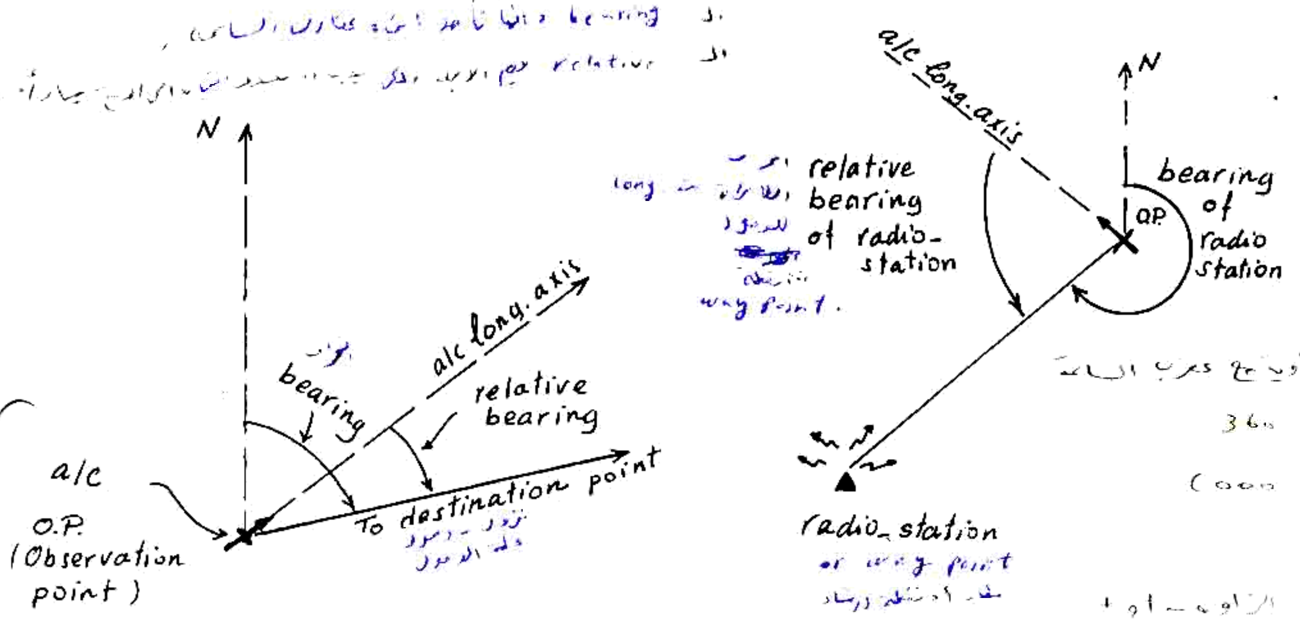
Track : means past line along which the craft has travelled. Track intended or required may denote future line. The track-angle (T_T) is the angle between the north-reference and the ground speed vector in the horizontal plane taken in clockwise direction

Course or Heading : means future direction in which the craft will travel. Course made good may denote past direction.

1.4.3. The Bearing (or azimuth)

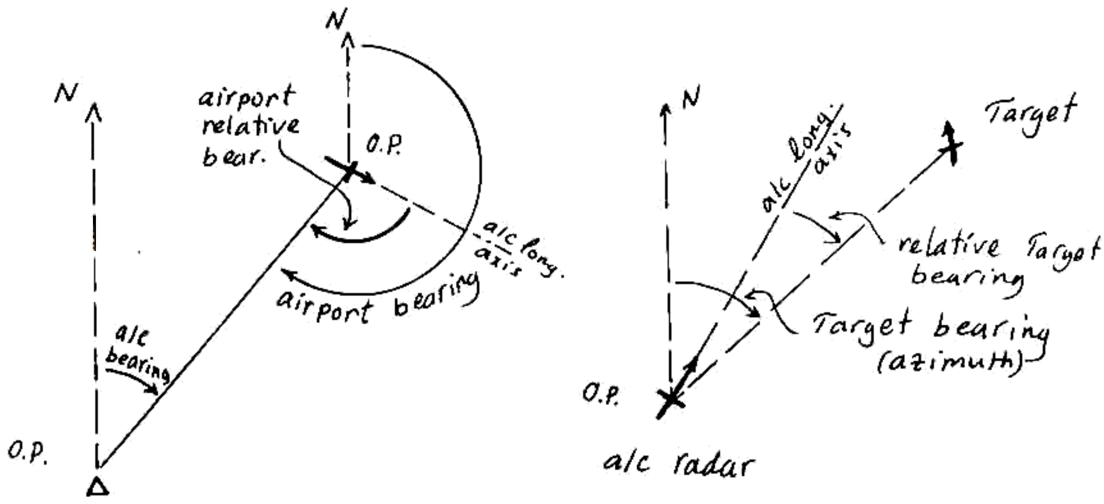
Bearing, is a direction in which a place lies. For air-navigation, the bearing angle is measured at certain observation point as the angle between the north-direction

at this point and the direction towards the object or place.
It is measured from 000° to 360° in clockwise direction.
The observation point may be an a/c, airport, way point, ground radar, etc, as shown in Fig. 1.18.



a- Bearing of destination point

b- Bearing of radio-station



c- a/c bearing & Airport-bearing

d- Target bearing.

Fig. 1.18. The Bearing & relative bearing

The true bearing is taken from the north-reference direction, while the relative bearing is taken from the longitudinal axis of the a/c as a reference direction. The relative bearing may be suffixed L or R or may have positive or negative sign. The relative bearing is the turn-angle of the a/c to get its direction or heading to the required point or target.

1.4.4. Altitude

The altitude of an aircraft must be known determing airspeed, for counting engine power, to maintain proper separation of flight paths for a/c flying in opposite directions, to measure adequate clearance over mountains and other flight obstacles extending upward from the ground, and for instrument flight. Altitude is very important in terminal navigation during take-off and landing beside the en-route navigation for terrain-avoidance or Terrain-following. There are three definitions of a/c altitude as shown in Fig. 1.19.

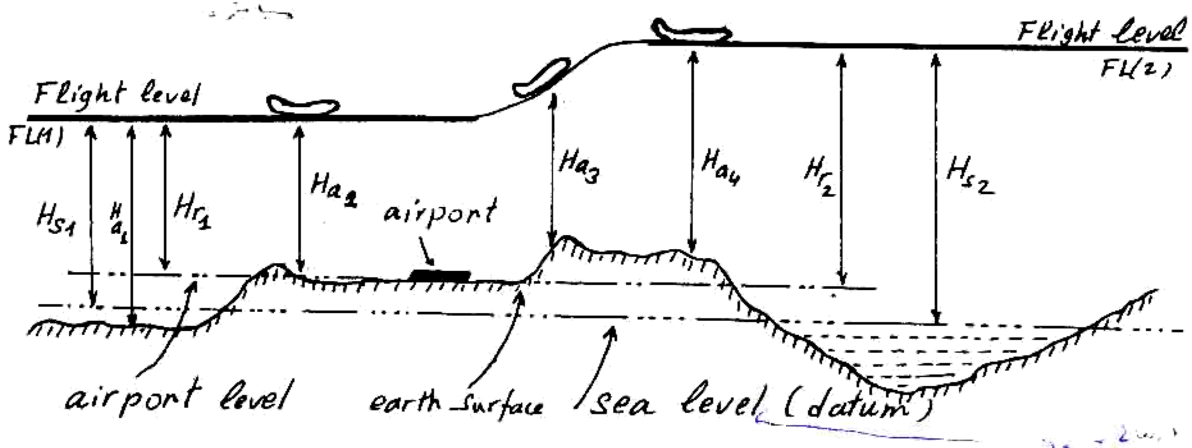


Fig. 1.19. Aircraft altitudes

a- The actual or absolute (real) altitude denoted in the figure by Ha is the distance (height) between the a/c and the ground under it. In the figure there are two flight levels FL1 & FL2, Ha is different from time to time according to the flight path and the earth-terrain. Actual altitude is measured only by radio-means.

b- The relative altitude (H_r), is the altitude relative to the airport level. It is of the same value for the same flight level; as shown in the figure, H_{r1} for flight level FL1 and H_{r2} for FL2.

c- The standard-pressure-altitude (H_s), it is the altitude relative to the standard sea-level pressure which has a pressure of 1013 mbar or 29.92 in Hg. The pressure-altitudes, like the relative altitudes, are of the same value for the same flight level. These types of altitudes; the relative and the standard pressure; are measured by a barometric-altimeter.

1.4.5. The Route (highway)

The aircraft route is the way taken or planned to travell from one place to another. To determine the route it is necessary to have charts on which we can draw the route. The route-determination gives us the possibility to calculate the course (direction) and the distance-travelled.

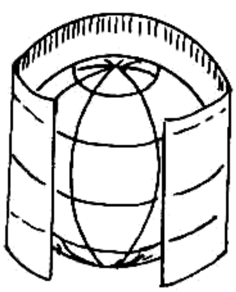
1.4.5.1. The charts

A chart is used for plotting the course of the craft,

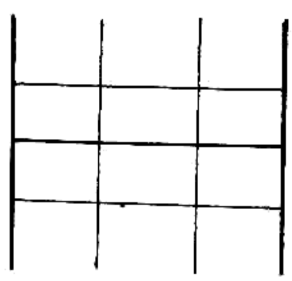
it is essential that directions are correctly represented all over the surface. A chart must therefore be free from angular distortion so that a protractor can be used anywhere over its surface. A chart with this characteristics is said to be "Orthomorphic" or "Conformal". Approximate constancy of scale is also useful. Over a small area, the projection is immaterial. Over a large area, four types of chart are commonly used.

a- Mercator: Orthomorphic. A rhumb-line appears straight. A rhumb-line on the surface of the earth is a line that cuts all the meridians that it acrosses at the same angle, it is known as "loxodrome".

The mercator is used with a magnetic, gyro-magnetic or gyro-compass. Scale is not constant. Adjacent sheets on the same equatorial scale will fit. The mercator chart projection is shown in Fig. 1.20 as a cylinder around the equator.



a. Mecator Projection

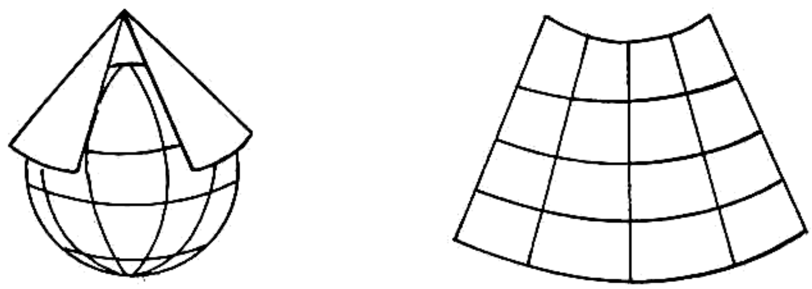


b- Mercator chart

Fig. 1.20. The mercator

b- Conical orthomorphic or "Lambert's conformal"

Instead of forming a chart as a cylinder around the equator, it my be formed as a cone around a prarallel of latitude, as shown in Fig.1.21, parallel of latitude known as the standard parallel.



a-Lambert projection   b-Lambert-chart

Fig.1.21. Conical, "Lambert"-chart

For the Lambert chart, Great circle appears as straight line approximately so that the projection is convenient for radio presentation and for steering with gyro heading reference - Approximates to constant scale.

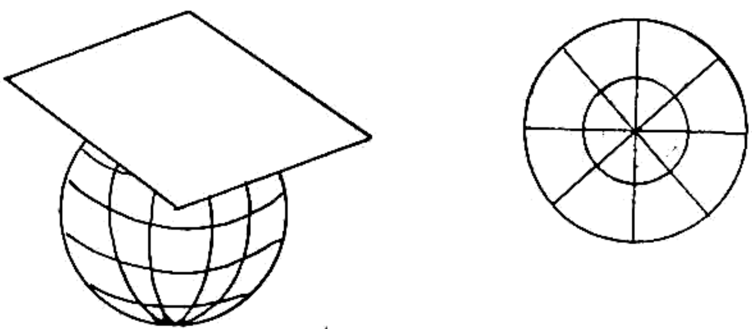
c- Polar stereographic

If the standard parallel of a conical orthomorphic chart were to be moved further away from the equator until it collapsed into a point at the pole, the cone would become a flat sheet and the projection would be a polar stereographic as shown in Fig. 1.22. It is used for polar grid navigation using gyro-heading reference

d- Transverse Mercator

If the mercator chart is based not on the equator but on some other great circle, it is known as an oblique

mercator. The chart will be orthomorphic, but the meridians will no longer appear as straight lines. A special example is the transverse mercator, sometimes known as a Gauss conformal that uses a meridian as the basic great circle, as shown in Fig. 1.23, such projection may be suitable for craft using a grid system of steering with a gyro-heading reference.



a - Polar projection　　b - Polar chart

Fig. 1.22. Polar stereographic

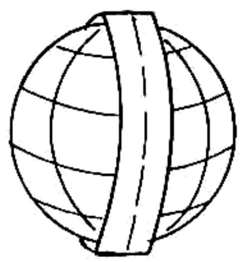


Fig. 1.23. Transverse Mercator

Charts are continually corrected and other information supplied through different organizations.

1.4.5.2. Routing: The route is chosen generally with two main points: avoidance of collision and economy of operations. Routing depends on: avoidance of flying into high ground, following of prescribed routes at prescribed heights, avoidance of head winds, bad weather and dangerous storms and icing, with the best use of navigational aids. In civil aviation, routing is generally determined by the requirements of air-traffic-control (ATC) authorities.

1.5. Basic aids

The development of navigation equipment, those devices which man uses to determine his position and course on the earth, roughly parallels the growth of his knowledge of the earth and the extent of the horizons fixed by his curiosity. The earliest navigation aids, as evidenced by maps of Egyptian gold mines dating from more than 3000 years ago, were prominent landmarks. These maps are little more than sketches showing prominent terrain features and such readily recognized man-made features as road junctions and monuments. Such navigation aids were adequate while travel was limited to one continent or to within sights of its coast. When travel involved crossing oceans or large seas, it become convenient to have aids substantially independent of recognizable landmarks. The basic aids to navigation may be classified into five groups: fundamental aids, astronomical, optical (visual), radio, and inertial aids.

1.5.1. The fundamental aids

These aids are based on utilization of various physical properties of the earth and its atmosphere, some examples are: - Earth's magnetic field is utilized to determine the magnetic north direction by means of the magnetic compasses

- Atmospheric pressure is utilized to determine the a/c altitude relative to sea-level or airport by the barometric altimeters-

- The dynamic and static pressure are utilized to

measure the a/c speed by means of the airspeed meter through a tube known as a "Pitot tube".

These aids have the following advantages:

- small weight and dimensions
- simple in construction, maintenance and services.
- self-contained or autonomous; they do not need other facilities from the ground
- Interference and jamming resistance

The major disadvantage of these aids is the accuracy, they have higher errors than other aids. Inspite of this disadvantage, they are used in all kinds of aircraft as primary aids.

1.5.2. Astronomical aids

The Sun, Moon and planets are generally as astronomical bodies and for convenience may be regarded as being on the celestial sphere, as shown in Fig.1.24. a hollow globe of great size within which the earth rotates. The position of a particular body on the celestial sphere and the orientation of the earth within it is tabulated for each instant of time in books of tables known as almanacs. It is therefore possible to find the point on the earth's surface above which is the particular body.

The positions of reference stars are charted using the celestial sphere. The principal features of this sphere are the celestial poles, alined with the earth's north-south axis; the celestial equator, a projection of the earth's

equatorial plane; and the plane of the ecliptic, the apparent yearly path of the sun around the celestial sphere.

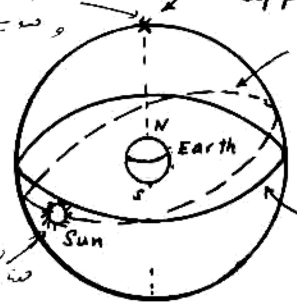


Fig. 1.24. The Celestial sphere

Since ancient times, the stars have been used to navigate and reckon position. The independence of the steller fix from external aids and initial conditions is a major reason for using star trackers in an a/c navigation by position fixes and, or azimuth monitor and correction.

The astronomical aids are self-contained, and have an interference resistance, but they need a bright sky and relatively long time for measurement and data processing for necessary calulations.

1.5.3. Optical (Visual) aids

The brain tends to interpret information from the eyes in accordance with what it expects to see. Hence visual identification must be achieved by combining unmistakable features and not by general impressions.

The marine charts is suitable for visual navigation

at sea. The air chart can only contain a limited amount of visual navigation information and therefore visual navigation generally, requires a topographical map, the features being selected according to significance when viewed from the air.

Coastal lights use simple codes for identification. Aerial lights are more widely spaced and use Morse codes. Buoys are identified by shape, colour and sometimes by sound.

Visual methods are valuable for collision avoidance because they assist the navigator to know what the target is likely to do. Navigation lights are used at night which assist the navigator to judge the aspect of a target.

Visual information may be used for landing and take-off. Special lighting systems are used to assist approach and landing at night as shown in Fig. 1.25.

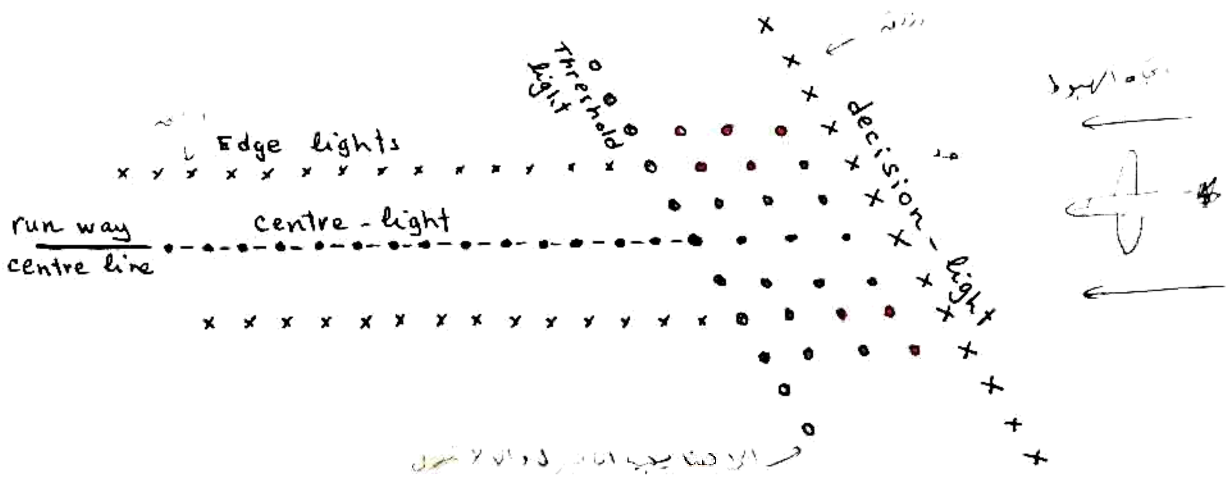


Fig. 1.25 Light system for landing

Lasers can be used for accurate range-finding for aiming weapons and for doppler speed measurements of targets. The ring-laser can act as a gyroscope.

Infrared has potentiality for identification of military targets, infrared devices may be used for satillite stabilization.

1.5.4. Radio aids

These aids are based on utilization of laws of radio waves and the propagation characteristics through the atmosphere.

These aids include: radiocompasses, radio altimeters, range measuring systems, ground-speed meter, landing systems, and many other systems used by all types of today a/c.

Radio aids have the following advantages:

- independence of operations on daytime and weather conditions
- high accuracy and high speed of measurements
- high speed in signal processing and calculations.

They have the following disadvantages:

- relatively complicated constructions, service and maintenance
- Possibility of interference and jamming
- They need ground beacons (transmitters) mainly for their operations, it means, most of them are not self-contained. We deal with their principles in the next chapter.

1.5.5. Inertial aids

Inertial navigation aids, self-contained, independent of electromagnetic radiation and the earth-magnetic field, are the contribution of modern technology to progress a kind of navigation known as "dead-reckoning". These systems require no wind or ocean-current data, no detectable radiation, no magnetic compass, no time-shared usage of ground facilities, no operator time during flight, and no special maps.

Their accuracy; independent of operating altitude and terrain; is limited almost solely by the accuracies of their component instruments.

Inertial navigation is a technique for determing a vehicle's position and velocity by measuring its acceleration and processing the acceleration information in a computer for double integration to obtain distance travelled, then projecting the distance into the travelled directions, we obtain the position. The direction measurements are obtained by gyroscopes, while the acceleration measurements by accelerometers.

These aids have the following disadvantages: بعكس

- The position and velocity information degrades with time. This is true whether the vehicle is moving or stationary — يجب توفر ضبط اولي قبل التشغيل و
- The equipment are expensive — errors تزداد مع التشغيل
  ، مطلقا
- Initial alignment is necessary

Inertial navigators are widely used in military vehiches. The first commercials uses is on the Anglo-French "Concorde" and the "jambo-jets". We deal with the principles of inertial navigation in chapter-3.

1.6. Kinds of navigation

Many ways of determing navigational information have been devised. All position-determination schemes can be classified as either dead-reckoning or position-fixing.

1.6.1. Dead-Reckoning

Dead reckoning consists of extropolation of a "known" position to some future time. An early method, still in use, utilizes an airspeed meter and compass. The information is utilized by means of hand computation or plotting on a chart.

Thus, if a person knew that he had travelled due east (090°) at a rate of 500 knots, he would know that at the end of half an hour he would be 250 miles east of the point of departure. If the coordinates of the starting point were known, those of the point of arrival could be readily determined, as shown in Fig. 1.26.

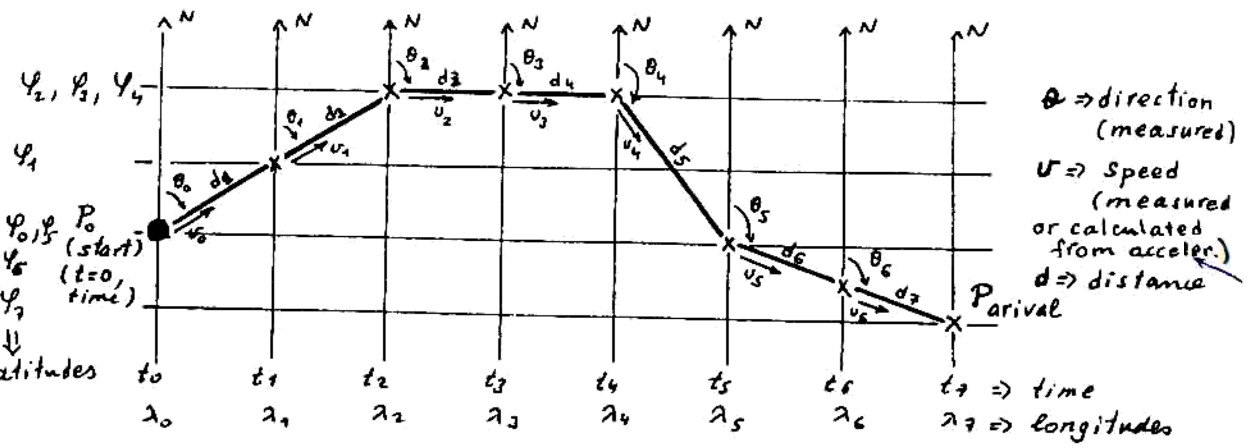


Fig. 1.26. Principle of dead-reckoning navigation

The first step toward automating this process consisted of interconnecting a true-airspeed meter, gyromagnetic compass, and analog dead-reckoning computer to form an automatic air-position-indicator system. The next step was to produce

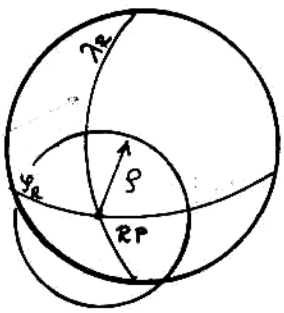
an automatic ground-position indicator system by interconnecting a Doppler radar (for ground speed measurement), compass, and dead-reckoning computer. The inertial plateform that measures directions and accelerations, is a useful part of a modern dead-reckoning system.

Dead reckoning has been characterized as the basis of all navigation, with position fixing constituting a method of updating it. Actually, dead reckoning and position fixing complement each other, each providing an independent means of checking the accuracy of the other. Where position fixing is intermittent, with relatively long intervals (e.g. hours) between fixes, dead-reckoning is approperiately considered the primary method. If fixes are available continuously or at very short intervals, the primary method might then be either dead-reckoning or position fixing or an integrated output from both.

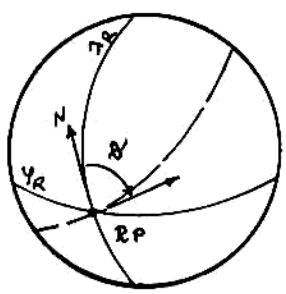
1.6.2. Position fixing

In contrast to dead reckoning, position fixing is the determination of the position of the craft (a fix) without reference to any former point. There are a number of ways in which this is complished. Perhaps the most common is by individual measurements, each of which establishes a line-of-position (LOP), a line on which the a/c is presumed to be located. The line might be a small circle, great circle, hyperbola, or other curve constituting the intersection of the surface of the earth (or a concentric surface at the altitude of the a/c) with a plane, cone,

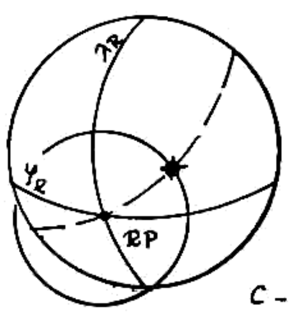
hyperboloid, etc. The common intersection of two or more nonparallel lines of position constitutes the fix. Fig. 1.27 shows the intersection between line of constant distance (sphere with radius ρ and centre at reference point RP) and line of constant bearing (great circle with bearing θ at RP)



a - LOP of constant distance from a fixed point



b - LOP of constant bearing at a a fixed point



c - a fix, intersection between LOPs of a and b

Fig. 1.27. Principle of position fixing

If the lines are determined at different times, one or more must be adjusted for the assumed motion during the interval between observations (dead-reckoning), to provide a running fix. Lines of position may be determined by observing the elevation angle of celestial bodies, measuring the direction or distance to a recognized landmark of known location (as shown in Fig. 1.26 for the reference point RP as a landmark), passing directly over an identifiable line such as a river or a highway or any of a multiplicity of radio aids.

Other navigational aids use map matching, in which the mosaic of features surrounding the a/c - determined visually, by radar, or by some other technique - is matched to a similar, previously determined mosaic.

Occasionally, an actual position is not needed, a line of position being adequate to insure safety. An example is the following of a line of position know to pass through the destination. This is called homing. The method is not suitable when other a/c are in the vicinity and a means of avoidance is not available.

1.6.3. Guidance

When navigation outputs are compared with a previously planned schedule and the differences are fed into the autopilot's intervention, the result is a guidance system. It is essential for an unmanned missiles or aircraft, and increasingly desirable for manned aircraft as speeds increase and traffic density becomes greater, requiring quicker

response to error indications and more accurate track-keeping capability.

Guidance itself may be as simple as riding a beam, or it may be sophisticated system consisting of one or more positioning systems suppling inputs to a computer. The actuation of the controls in response to the guidance system output is accomplished by the control system.

1.6.4. En-route and terminal phases

Navigation may also be classified according to the portion of flight involved. separate aids with different characteristics are generally used for the en-route and terminal phases.

During the en-route phase one may use a series of ground-referenced short-distance aids with relatively high accuracy but with coverage limited to line-of-sight distances. Over oceans and underdeveloped land areas such as polar regions long-distance aids are used. These have traditionally been ground-referenced aids of lower accuracy than short-distance aids. In most cases, they have provided intermediate accuracy fixes, for use with dead-reckoning. With traffic density increasing in such areas, the requirement for continuous position determination and greater accuracy becomes greater. self-contained aids providing automatic dead-reckoning capability become increasingly attractive as their accuracy and reliability increase and cost

decreases.

As an a/c approaches a terminal and proceeds in for landing, it enters an area of converting tracks and high density traffic where high accuracy, both horizontally and vertically, becomes essential, with continuous indication.

Navigation requirements become accentuated as visibility limits are lowered to provide service in virtually any weather.

1.6.5. Vertical navigation

A distinctive feature of air navigation, as contrasted with that of surface craft, is its three dimensional aspect. The altitude of the en-route portion of a flight is established primarily by the operational characteristics of the aircraft. For propeller-type craft cruise most efficiency below 25,000 feet; subsonic jets, between 25,000 and 45,000 feet, and supersonic jets, at 50,000 to 80,000 feet. This fortunate situation provides natural separation of a/c in different speed ranges, thus contributing to air safety. Within each class further vertical separation is provided arbitrary by the air-traffic control system

air traffic control
ATC

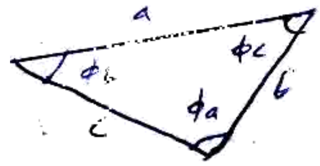
1.6.6. Navigation, Surveillance, and Communication

Safety and efficiency in utilization of airspace are enhanced by a system of air-traffic-control (ATC)

Ground-based controllers attempt to maintain communication with all aircraft in the controlled airspace. The controllers are able to provide instructions to the pilots by means of air-derived navigational and collision-avoidance information transmitted to the ground by means of ground-derived positional information determined by surveillance radar and ground-based direction finders, and by means of flight plans filed in advance by pilots.

Air-derived navigational information, ground-derived surveillance, and communications are interrelated. An increase in the accuracy and dependability of air-derived information lessens the need for communications and surveillance, and vice versa. The modern air-traffic-control systems are composite of a number of aids all complementing one another.

$$\frac{a}{\sin \phi_a} = \frac{b}{\sin \phi_b} = \frac{c}{\sin \phi_c}$$



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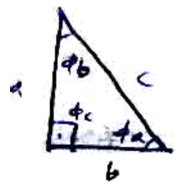
$$\sin \phi_b = \frac{b}{c}$$

$$\cos \phi_b = \frac{a}{c}$$

$$\tan \phi_b = \frac{b}{a}$$

$$c = \sqrt{a^2 + b^2}$$



قوانين خاصة بالمثلث فقط
اذا كان المثلث قائم الزاوية .

اتجاه longitudinal axis of the aircraft = اتجاه V_a

$$\text{cource angle} = T_T + \delta$$

bearing angle or azimuth = هي الزاوية المحصورة بين N الطائرة وبين الخط الواصل بين الطائرة والنقطة التي عندها الـ bearing angle وتكون باتجاه عقرب الساعة .

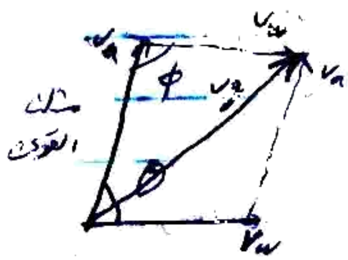
relative bearing angle: هي الزاوية المحصورة بين الـ long axis الطائرة والخط الواصل بين الطائرة والنقطة التي نقاس عندها الـ relative bearing angle
وتكون باتجاه او عكس اتجاه عقرب الساعة .
اذا كانت باتجاه عقرب الساعة تكون موجبة
" " " عكس " " " سالبة .

$V_g =$ محصلة بين V_a & V_w

T_T = Track angle بين V_g & N

δ = drift angle بين V_g & L_{ang} axis of ac

أو بين V_g & V_a



$\theta + \phi = \pi$

$(\pi - \theta) = \phi$

$$V_g = \sqrt{V_a^2 + V_w^2 + 2 V_a V_w \cos\theta}$$

$$V_g = \sqrt{V_a^2 + V_w^2 - 2 V_a V_w \cos\phi}$$

قوانين عامة تنطبق على اي مثلث

Review Questions

Chapter - 1

1.1 - What are the functions of the avionics engineers ?

1.2 - What are the differences in navigation functions in the past, present and future times?

1.3 - Mention different types of craft that can be navigated?

1.4 - What are the effects of the earth-rotation at different places ?

1.5 - What are the temperature limits expected for avionics equipment ?

1.6 - Why the scale of the barometric altimeter is not linear?

1.7 - What are the weather-effects and the need for forcasting in the navigation ?

1.8 - What is the refference - ellipsoid ?

1.9 - Differentiate between geodetic, geocentric and astronomic latitudes.

1.10 - What are the differences between geodetic and geocentric spherical coordinates ?

1.11 - What coordinate is suitable for?:

a - A/C near the north pole

b - A/C flies along great circle near the ground

c - A/C flies inside a limited region near an airport.

1.12 - What are the functions of the attitude and heading references ?

1.13 - Define the following terms :

a - Sideslip angle, b - drift angle, c - Track angle

d - earth speed, e - heading, f - course

1.14 - What is the difference between bearing and the relative bearing ?

1.15 - Show the different definitions of a/c altitude, what is suitable for landing ?

1.16 - What is meant by an "orthomorphic" charts?, give an example.

1.17 - Compare between different navigation - aids from the following points of view :

- Simplicity. - Accuracy. - jamming resistance.
- initial conditions. - Measuring time. - cost.

1.18 - What is the role of communications played for the navigation - purposes?

1.19 - Compare between dead - reckoning and position - fixing.

1.20 - What is the function of an air - traffic - control (ATC) authority ?

Problems

P.1.1 - An aircraft keeps its flight - level and speed at 1000 km/h, starts from point A with course 030 for 10 minutes to point B. At B it changes its course to 120 during 15 minutes to point C. The wind is horizontal during the whole flight with speed 50 m/s and azimuth 300 as shown in Fig. P.1-1. Find :

a - Track - angle, drift - angle, and ground speed at points A and B

b - Time and course from point C to go-back to A.

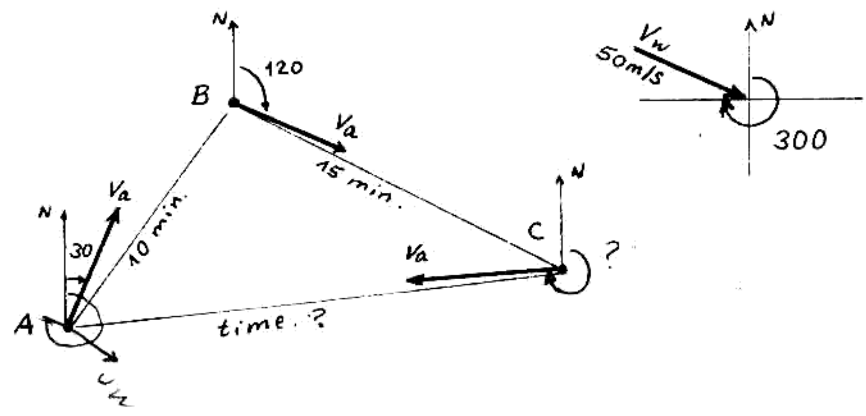


Fig. P. 1-1.

P.1.2 - An aircraft at point A with relative altitude 80.000 ft, distance 300 nm and bearing 300 from an airport at point O. It starts to fly with relative bearing 60° (right) for 10 minutes to point B in the same flight level. At B it changes the course to 090 with dive angle 30° for 1 minute, then it keeps the flight level for 20 minutes with the same course to point C. The air speed 500 knots is kept constant, the wind is horizontal of speed 100 knots with azimuth 270 for the whole flight, as shown in Fig. P. 1-2. Find:

a - Track angle, drift angle and ground speed at points A and B

b - Change of course and relative-bearing to go to point O from point C

c - time to reach point O and its altitude at the airport.

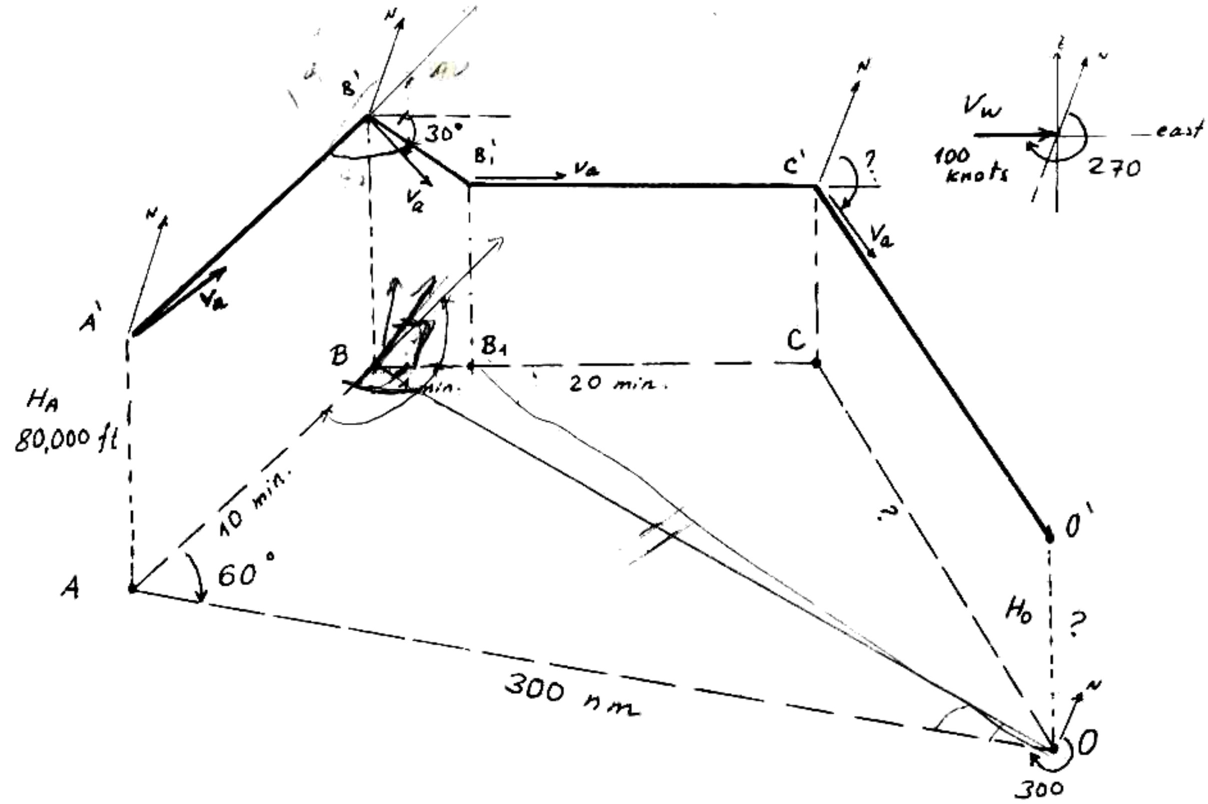
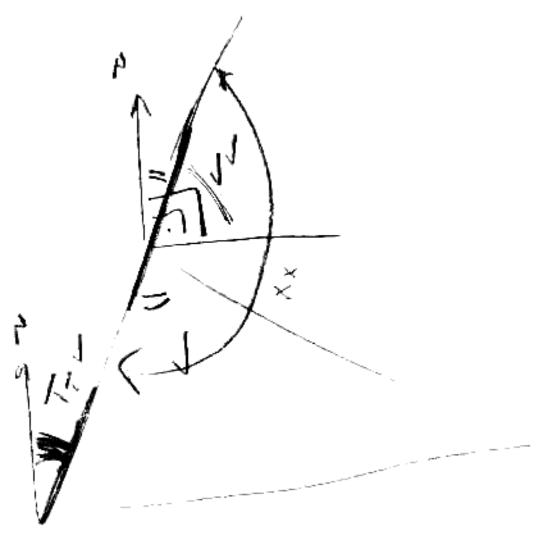

N
B'
30°
B1'
Va
C'
?
N
Vw
100 knots
east
270
A'
Va
B
B1
20 min.
C
HA
80,000 ft
10 min.
?
O'
A
60°
HO
?
300 nm
O
300

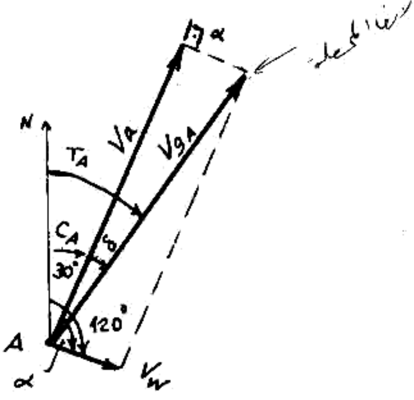
Fig. P. 1. 2

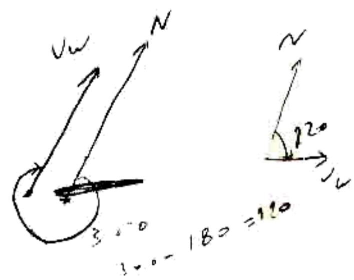

N
A

Solution of problem P.1.1

- At point A

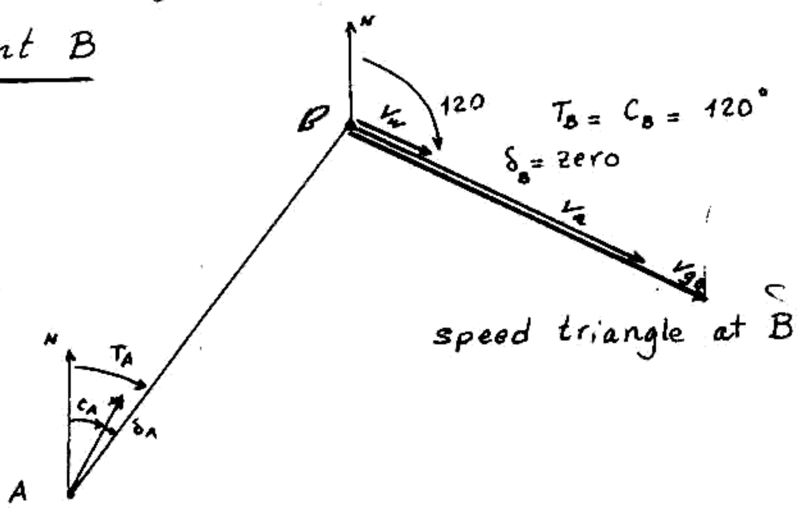
Speed triangle at point A





- $V_w = 50 \ m/s = \frac{50 \times 60 \times 60}{1000} = 180 \ km/h$
- angle between V_w and V_a , $\alpha = 120 - 30 = 90°$
- * $V_{g_A} = \sqrt{V_a^2 + V_w^2 + 2 V_a V_w \cos\alpha} = \sqrt{V_a^2 + V_w^2} = 1016.07 \ km/h$
- * $\delta_A = \sin^{-1}[(V_w / V_g) \sin\alpha] = 10.2°$
- * $T_A = C_A$ (course angle) $+ \delta = 30 + 10.2 = 40.2°$
- distance $\overline{AB} = V_g \cdot t_{AB} = 1016.07 \times (10/60)$
  $= 169.345 \ km$

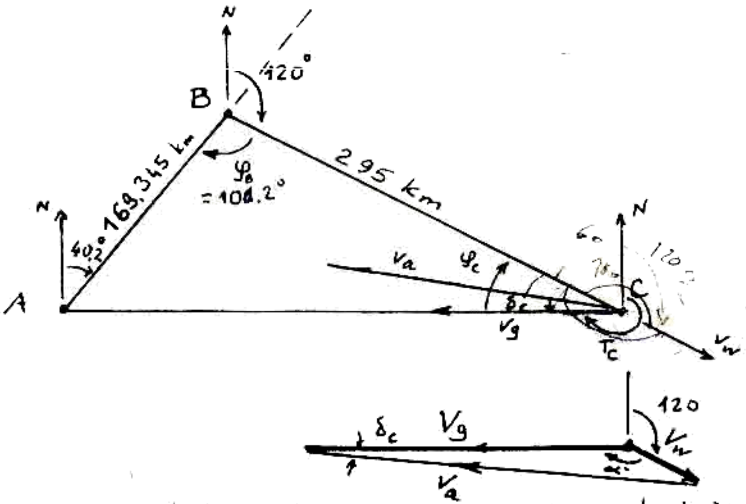
- At point B



speed triangle at B

- * $V_{g_B} = V_a + V_w = 1180 \ km/h$
- * $T_B = C_B = 120°$
- * δ_B = zero (Track)
- distance $\overline{BC} = V_{g_B} \cdot t_{BC} = 1180 \times (15/60) = 295 \ km$

- At point C



speed triangle at C

* Solution of triangle ABC
  - the angle $A\hat{B}C = \varphi_B = 180 - (120 - 40.2) = 100.2°$
  - distance $\overline{CA} = \sqrt{(\overline{AB})^2 + (\overline{BC})^2 - 2(\overline{AB})(\overline{BC})\cos\varphi}$

    $= 367.572$ Km
  - the angle $B\hat{C}A = \varphi_c = \sin^{-1}\left(\frac{\overline{AB}}{\overline{AC}} \sin\varphi_B\right) = 26.868°$
* - Track angle $T_c = 120 + (180 - \varphi_c) = 273.132°$
  - Angle between V_g and V_w, $\alpha` = T_c - 120 = 153.132°$
* The speed triangle at C
  - $\delta_c = \sin^{-1}[(V_w / V_a)\sin\alpha`] = 4.666°$
* - Course angle at C $C_c = T_c + \delta_c = 277.798°$
  - $V_{g_c} = V_a \sin(\alpha` + \delta_c) / \sin(\alpha`) = 836.12$ km/h
* - time $t_{CA} = \overline{CA} / V_{g_c} = 26.377$ minutes