Chapter 7

AIRCRAFT NAVIGATION

Keywords. Navigation, Dead-reckoning, Position-fixing, Celestial navigation, LORAN, VOR

7.1 INTRODUCTION

Navigation may be considered as the art of directing the movement of a vehicle from one place to another. It is an art practiced by all who travel but its development is rooted firmly in the fundamental laws of science. In today's context it can be formally defined as the determination of a strategy for estimating the position of a vehicle along the flight path, given outputs from specified sensors.

In the early days, when man-made vehicles were surface bound (either on land or in the sea) and they seldom ventured far beyond easily recognizable landmarks, the act of navigation could be carried out by humans using their senses to determine direction distance, speed, and position. As vehicles became more and more sophisticated and their field of operation expanded to realms beyond the perception of limited human senses sophisticated navigation instruments became necessary. Instead of known landmarks these instruments used information learned from celestial bodies, certain distant objects on the surface of the earth, and many other sources of information to carry out the job of navigation.

In these lecture notes we shall exclusively focus on the navigation of aircraft. Whenever a purposeful change in location has to take place for an aircraft the following questions must be asked and answered:

∗ Where is the aircraft now?.

∗ (or, more specifically) where is the aircraft now with respect to where it should have been?

These questions are answered by a navigation system. There are a number of reasons why sophisticated navigation systems have become so important in modern times. Some of them are.

∗ Time lags between measurement and decision needed to be reduced.

∗ Number of aircraft in a given airspace has increased manifold in the past few decades.

∗ Safety requirements have become crucial.

A navigation system may provide information in a variety of forms, appropriate to the needs of the aircraft. If the information is primarily for the benefit of the crew. it involves some type of display. other outputs, however may involve steering signals sent directly to the autopilot or digital information sent to a central computer. However in the modern context one would consider these systems as navigation-cum-guidance systems. Some of the forms that this information takes are given below.

Position Information: The basis of virtually all navigation outputs is position. position can be given in geographic coordinates-geodetic latitude (ϕ), geodetic longitude (λ), and altitude (h) - as in en-route navigation for long distance flights, or as polar coordinates with a ground-based navigational aid as the origin, as in terminal areas.

Steering Information : Due to crowding of the airspace one of the major tasks that an aircraft pilot has to perform is keeping out of the way of other aircraft. The technique widely used now-a days involves the assignment, to each aircraft, of a block of air having established dimensions called lateral, longitudinal and vertical separation. The exact dimensions depend on the instruments in use, the speed and character of the aircraft and the flight environment too. This block moves at the speed indicated in the aircraft's flight plan. It is the task of the pilot to remain within this block. Consequently the pilot needs to know, at any time, where he is with respect to this block of air. The desired output is a continuous, real-time indication of where the aircraft is with respect to the center of the assigned block. With intermittent fixing (in which intermediate checking points are established), the total error for which the system must allow consists of the error in position determination, plus the accumulated error between measurements and action based on determination of position and interpretation of results.

Displays : Navigational information must be made available to the pilot in a form suitable for his use. when navigation was mainly a manual operation, the usual display consisted of a chart, or plotting sheet, on which lines of position and fixes were plotted with higher speeds and increased traffic density, such a display is no longer adequate. Modern displays are basically computer-based and depend on some kind of CRT display, or advanced flat planar color displays. HUD (Head Up Display) is one such electronic and optical instrument which provides the pilot with such essential functions as aircraft performance information, navigation and landing guidance, on a single display in symbolic form.

7.2 TYPES OF NAVIGATION

All position-determination schemes can be classified as either dead reckoning or Position fixing.

Dead Reckoning

Dead reckoning consists of extrapolation of a 'known' position to some future time. It involves measurement of direction of motion and distance traveled. The actual computation is performed by taking the last known position and the time at which it was obtained, noting average speed and heading since then and the present time. The speed is usually resolved to get North and East components and each is multiplied by the time elapsed since the last position to get distance traveled. This can be added to the initial position to get the present position. To perform all these functions the Navigation system requires the following instruments: (1) A speed measuring device (2) A heading sensor (3)A timer and (4) A computer.

Measurement of speed is usually done using an air-speed meter (which measures the aircraft's speed relative to the air and does not take into account the speed of the air relative to the surface of the earth), or by measuring the ground speed using doppler effect (this is done by transmitting three or four beams in different directions toward the ground and measuring the aircraft's relative velocity along these beams - see Problem 1 at the end of the chapter). Heading can be measured using a simple magnetic compass, a gyro-magnetic compass, or a gyrocompass.

The dead-reckoning computations are done as follows: Assume that the measurements of ground speed V_g and true heading θ_T has been done accurately. Then, with reference to Fig. 7.1,

$$V_{north} = V_g \sin\theta_T \qquad Y - Y_o = \int_o^t {V_{north}}^{dt} \tag{7.1}$$

$$V_{east} = V_g \cos\theta_T \qquad X - X_o = \int_o^t V_{east}{}^{dt} \tag{7.2}$$

where, t is the measurement interval and (Y-Y_o) and (X-X_o) are the distances

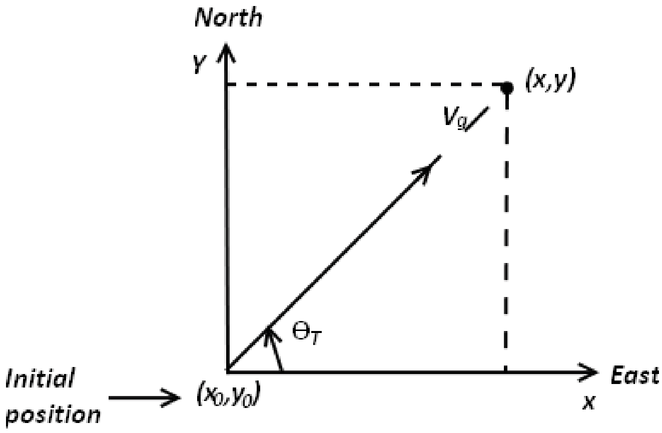

Figure 7.1: Dead-reckoning computations

traveled due north and due east during this measurement interval. Notice that a simple integration of unresolved ground speed $1/V_g$ would give curvilinear distance traveled but would be of little use for determining position. Thus, one must integrate the velocity.

The above equations are extremely simplified and are given only to impart an idea of the principle on which the dead reckoning system works. In reality the actual dead reckoning computer must also account for cross winds, the kinematics of the aircraft, its angular orientation, the geometry of the earth and its attendant gravitational effects, and many other factors before it can extrapolate in a reasonably accurate manner.

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 position. There are three basic methods of fixing position : (1) Map reading (2) Celestial navigation and (3) Measuring range and/or bearing to identifiable points.

Map reading involves matching what can be seen of the outside world with a map and is the traditional method of position fixing on land and is also used by general aviation in clear weather. Modern systems adopting this technique uses a radar to obtain a picture of the ground from the air and a computer matches it with a map stored in the form of a digital land mass database. These system are called terrain referenced navigation aids.

Celestial navigation has been used by mariners for centuries. The basis of celestial navigation is that if the altitude of a celestial object (measured in terms of the angle between the line-of-sight and the horizontal) of a celestial object is measured then the observer's position must lie on a specific circle

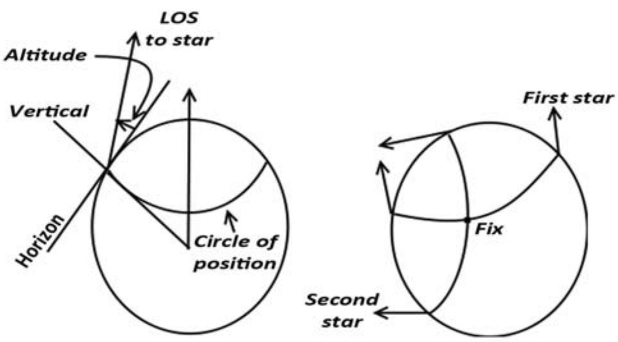

Figure 7.2: Celestial navigation

(called the circle of position) on the surface of the earth centered on the point on the earth which is directly below the object. This is shown in Fig.7.2. If the time of observation is noted and the celestial object is a star then this circle can easily be found using astronomical tables and charts. Sightings on two or more such celestial objects will give two or more such circles of position, and their intersection will give the position of the craft. Though in the early days some aircraft did use celestial navigation this has been abandoned nowadays in favour of better navigational aids. However, we shall show that its basic principle (that of intersection of circles of position to determine the exact position) will be used in a more general form in more advanced navigation system.

Range and bearing navigational techniques are the basis of most modern position fixing systems. They use modern electronic equipment for doing this kind of measurement. Through individual measurements of range and bearing, a line of position a line on which the craft is presumed to be located-is established. In principle, it is somewhat similar to celestial navigation. The line might be a small circle, great circle, hyperbola or some other curve constituting the intersection of the surface of the earth (or a concentric surface at the altitude of the aircraft) with a plane or a cone or a hyperboloid etc. The common intersection of two or more nonparallel lines of position constitutes the fix. If the lines are determined at different times, then one or more of them must be adjusted for the assumed motion during the interval provide a running fix. Occasionally, an actual position is not needed, a line of position being adequate to ensure safety. This is called homing. The method is not suitable when other aircraft are in the vicinity and a means of avoiding them is not available.

Before we go on to describe some widely used navigational aids we would like to discuss a few important points. 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 (often hours) between fixes, dead reckoning is appropriately considered the primary method. If fixes are available continuously or at very short intervals (e.g., once each minute), the primary method might then be either dead reckoning or position fixing or an integrated output of both.

Another classification of navigation may be according to the portion of flight involved. Usually, this classification is done as En-route phase and terminal phase.

In the en-route phase a series of ground-referenced short distance aids with relatively high accuracy but with coverage limited to line-of-sight distances may be used. The International Civil Aviation Organisation (ICAO) recommends, as standard short-distance aids the very-high-frequency omnidirectional range (VOR) and distance measuring equipment (DME). Over oceans and underdeveloped land areas such as polar regions (having no distinguishable land marks), long distance aids which are of lower accuracy than short distance aids are used. In most cases they provide intermediate accuracy fixes for use with dead reckoning. But with the increasing density of air traffic in such regions, automatic dead reckoning units of greater accuracy become increasingly important.

In the terminal phase when an aircraft approaches terminal and proceeds to a landing , it enters an area of converging 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.

In the next few sections we shall discuss a number of navigation systems currently in use for aircraft navigation.

7.3 THE LORAN SYSTEM

The LORAN (Long-Range-Navigation) is a position fixing aid. It operates on a single frequency of 100 Khz and has a long range (greater than 1200 km). The latest version of this system called LORAN-C is very widespread, having many chains throughout the continental USA, much of Europe and the Middle East. The European countries, as well as the Russians have confirmed their intention to use and expand LORAN-C (and the Russian equivalent called Chayka)as a primary radio-navigation source. On August 6 1992, six nations in the European Community signed a treaty to expand LORAN-C coverage. Installations of LORAN-C chains by the governments of India and China indicate the worldwide interest in LORAN.

The basic principle of LORAN is simple. Each LORAN chain consists of a master station and two, three or more slave stations. The aircraft receiver must be tuned to select a chain (of master and slave stations) by manual or by computer selection.Each chain transmits a sequence of pulses. First the master and then after a fixed coding delay, the slaves (Fig.7.3). Each slave in a chain has a unique coding delay that allows the aircraft to receive its signal before any other slave transmits. Usually the master's signal is received by the slaves and retransmitted after the specified coding delay. The number of pulses (eight or nine) and the coding delay identifies the master and slaves of a given chain. the navigation computer in the aircraft is fed with the position information of the master and slave stations in a chain.

The receiver in the aircraft measures the difference between the time of arrival of the pulse from the master station and the slave stations. The time difference is measured using the third RF cycle in each pulse as the reference point (see Fig.7.3). The locus of points of constant time difference is a hyperbola-like line-of-position on the reference ellipsoid which models the surface of the earth. By using the master and a second slave a second

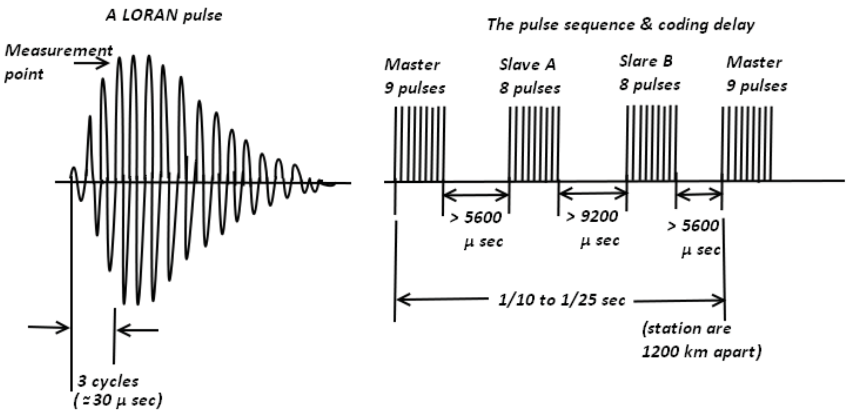

Figure 7.3: The LORAN-C pulses

hyperbola is obtained. The two hyperbolas intersect at the aircraft's position and at an ambiguous second point(Fig.7.4). The ambiguity can be resolved by using another slave and obtaining a third line-of position. However, the use of too many lines-of-position can lead to a possible region of location of the aircraft rather than a single point. this region is called a cocked hat in the marine terminology (Fig.7.5). This can also occur when a number of navigation aids are used (multi-sensor navigation). Due to the hyperbola-like lines of position LORAN is also called a hyperbolic navigation system.

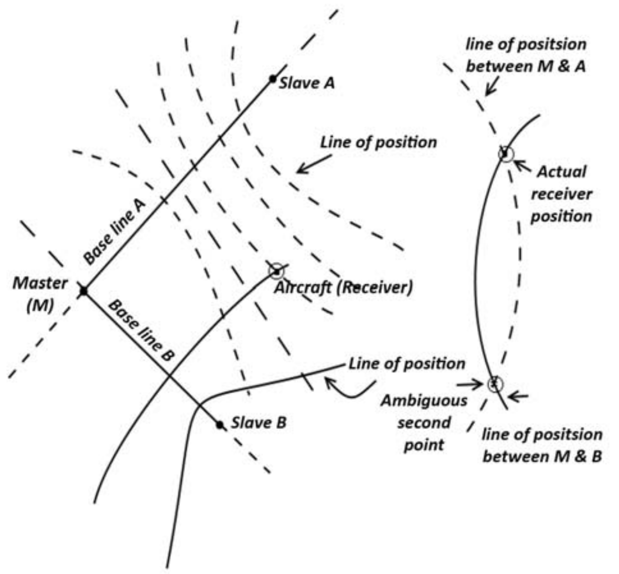

Figure 7.4: LORAN lines-of-position

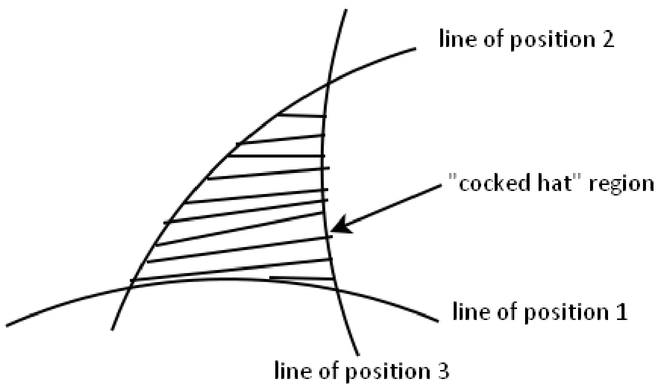

Figure 7.5: The "cocked hat"