Tishk International University Engineering Faculty
Mechatronics Engineering Department
AVIONICS

TOPIC: Navigation Systems

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Chapter 6
Navigation Systems

6.1 Introduction and Basic Principles

6.1.1 Introduction

The dictionary definition of navigation is a good one.

> *Navigation* – The act, science or art of directing the movement of a ship or aircraft.

Navigation thus involves both control of the aircraft's flight path and the guidance for its mission.

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The measurement of the aircraft's attitude with respect to the horizontal plane in terms of the pitch and bank angles and its heading, that is the direction in which it is pointing in the horizontal plane with respect to North, is essential for both control and guidance.

This information is vital for the pilot in order to fly the aircraft safely in all weather conditions, including those when the normal visibility of the horizon and landmarks is poor or not available, for example in haze or fog conditions, flying in cloud and night flying. Attitude and heading information is also essential for the key avionic systems which enable the crew to carry out the aircraft's mission. These systems include the autopilot system (e.g., Attitude and Heading Hold modes, Autoland, etc.) navigation system and the weapon aiming system. The information is also required for pointing radar beams and infrared sensors.

Position fixing navigation systems depend on external references to derive the aircraft's position. For example, radio/radar transmitters on the ground, or in satellites whose orbital positions are precisely known. Unlike DR navigation systems, their errors are not time dependent. The errors are also independent of the aircraft's position in most position fixing systems.

The main position fixing navigation systems in current use are briefly summarised below.

(1) *Range and Bearing ('R/θ') Radio Navigation Aids*

These comprise VOR/DME and TACAN.

VOR (VHF omni-directional range) is an internationally designated short-distance radio navigation aid and is an integral part of Air Traffic Control procedures.

DME (distance measuring equipment) is co-located with VOR and provides the distance from an aircraft to the DME transmitter.

TACAN is the primary tactical air navigation system for the military services of the USA and NATO countries. It is often co-located with civil VOR stations, such combined facilities being known as VORTAC stations. The systems are line of sight systems and provide the slant range of the aircraft from the ground station using a transmitter/transponder technique. A rotating antenna system at the TACAN ground station (or beacon) enables the aircraft to measure the bearing of the TACAN beacon to an accuracy of about 2°, using a principle analogous to a lighthouse.

Navigation position accuracy of VOR/DME and TACAN is of the order of one to two miles.

There used to be other radio navigation systems in operation which used a chain of ground based transmitting stations. The systems used pulse transmissions and operated by measuring the phase differences between the signals received from the different transmitter stations. They are referred to as *hyperbolic radio navigation systems*. These systems have been progressively discontinued over the years; OMEGA was discontinued around 2000 and the last remaining system, LORAN C,

(2) *Satellite Navigation Systems – GPS (Global Position System)*

GPS is the most important and accurate position fixing system developed to date. It is being used by every type of vehicle – aircraft – ships – land vehicles. Civilian use is now very widespread, for example, GPS receivers are fitted in very many cars, vans and lorries and they are readily affordable for ramblers.

The equipment required by the GPS user is entirely passive and requires a GPS receiver only. Electronic miniaturisation has enabled very compact and light weight GPS receivers to be produced. The full positional accuracy of 16 m (3D) and velocity accuracy of 0.1 m/s is now available to civil users (previously, only military users were able to achieve this accuracy). Precise time to within a few billionths of a second is also available.

The use of GPS in conjunction with a ground station system which transmits corrections to the user system, known as Differential GPS, has enabled a positional accuracy of 1 m to be achieved.

Construction of an independent, European system known as the Galileo satellite navigation system has begun and is scheduled to come into operation around 2014. The system will be inter-operable with GPS and with 40 orbiting satellites will provide an accuracy worldwide of the order of 1 metre.

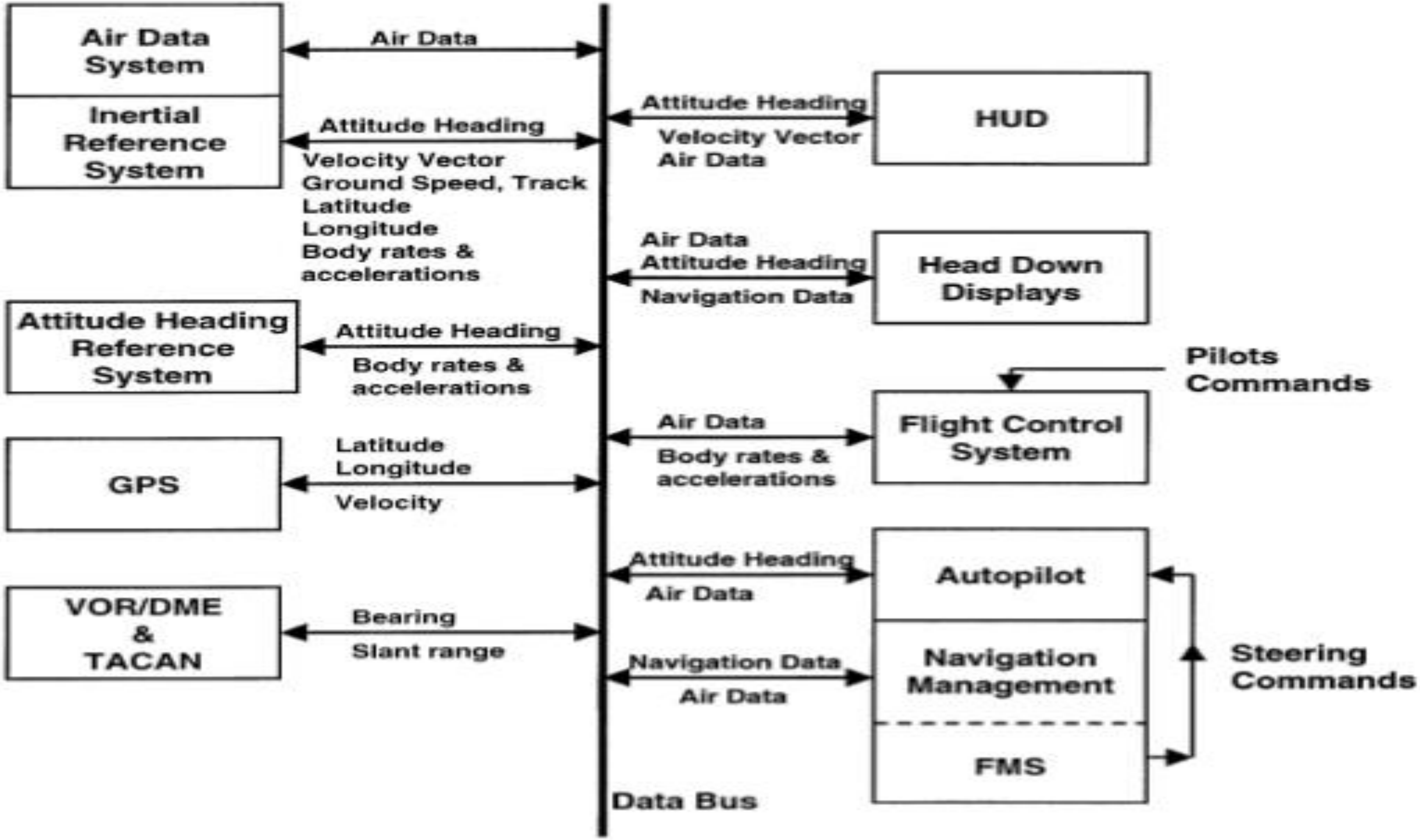

Fig. 6.1 Navigation system information flow to user systems.

(3) *Terrain Reference Navigation (TRN) Systems*

Terrain reference navigation systems derive the vehicle's position by correlating the terrain measurements made by a sensor in the vehicle with the known terrain feature data in the vicinity of the DR estimated position. The terrain feature data is obtained from a stored digital map database.

Figure 6.1 shows the information flow from the inertial sensor systems, air data system(s) and the position fixing radio navigation systems to the user systems.

The accuracy of the INS/IRS can be greatly improved by combining the inertially derived position data with that from a position fixing navigational source, such as GPS. This is achieved by using a statistical predicting filter known as a Kalman filter which provides an optimum combination of the two sources of data. The resulting combination is superior to either source on its own and retains the best features of each system. An introduction to Kalman filters is provided in Section 6.3.

6.1.2 Basic Navigation Definitions

A very brief review of the terms and quantities used in navigation is set out below. Position on the Earth's surface is generally specified in terms of *latitude* and *longitude* co-ordinates which provide a circular grid over the surface of the Earth. The Earth is basically a sphere – the variation in the radius of the Earth is only about 40 NM in a radius of 3,438 NM at the equator, being slightly flattened at the poles (this variation is taken into account in the navigation computations).

Referring to Figure 6.2, latitude and longitude are defined with respect to the polar axis, the equator and the prime meridian. A *meridian* is a circle round the Earth passing through the North and South poles. The *prime meridian* is the meridian passing through Greenwich which provides the datum for measuring the longitude. The *latitude* of a point on the Earth's surface is the angle subtended at the Earth's centre by the arc along the meridian passing through the point and measured from the equator to the point. The range of latitude angles is from 0° to 90° North and 0° to 90° South. The *longitude* of a point on the Earth's surface is the angle subtended at the Earth's centre by the arc along the equator measured East or West of the prime meridian to the meridian passing through the point. The range of longitude angles to cover all points on the Earth's surface is thus 0° to 180° east of the prime meridian and 0° to 180° west of the prime meridian. Latitude and longitude are expressed in degrees, minutes of arc, and seconds of arc.

Great circles are circles on the surface of a sphere with their centre at the centre of the sphere, that is, the plane of a great circle passes through the Earth's centre.

Meridians and the equator are thus great circles. Parallels of latitude which are circles round the Earth parallel to the equator, are, however, small circles.

The shortest distance between two points on the surface of a sphere is a great circle, hence navigation routes try to follow a great circle path. Navigation between points on the Earth's surface thus involves the solution of spherical triangles as shown in Figure 6.3 (a spherical triangle being defined as a triangle on a sphere whose sides are part of great circles. Their solution is achieved using the well established formulae of spherical trigonometry).

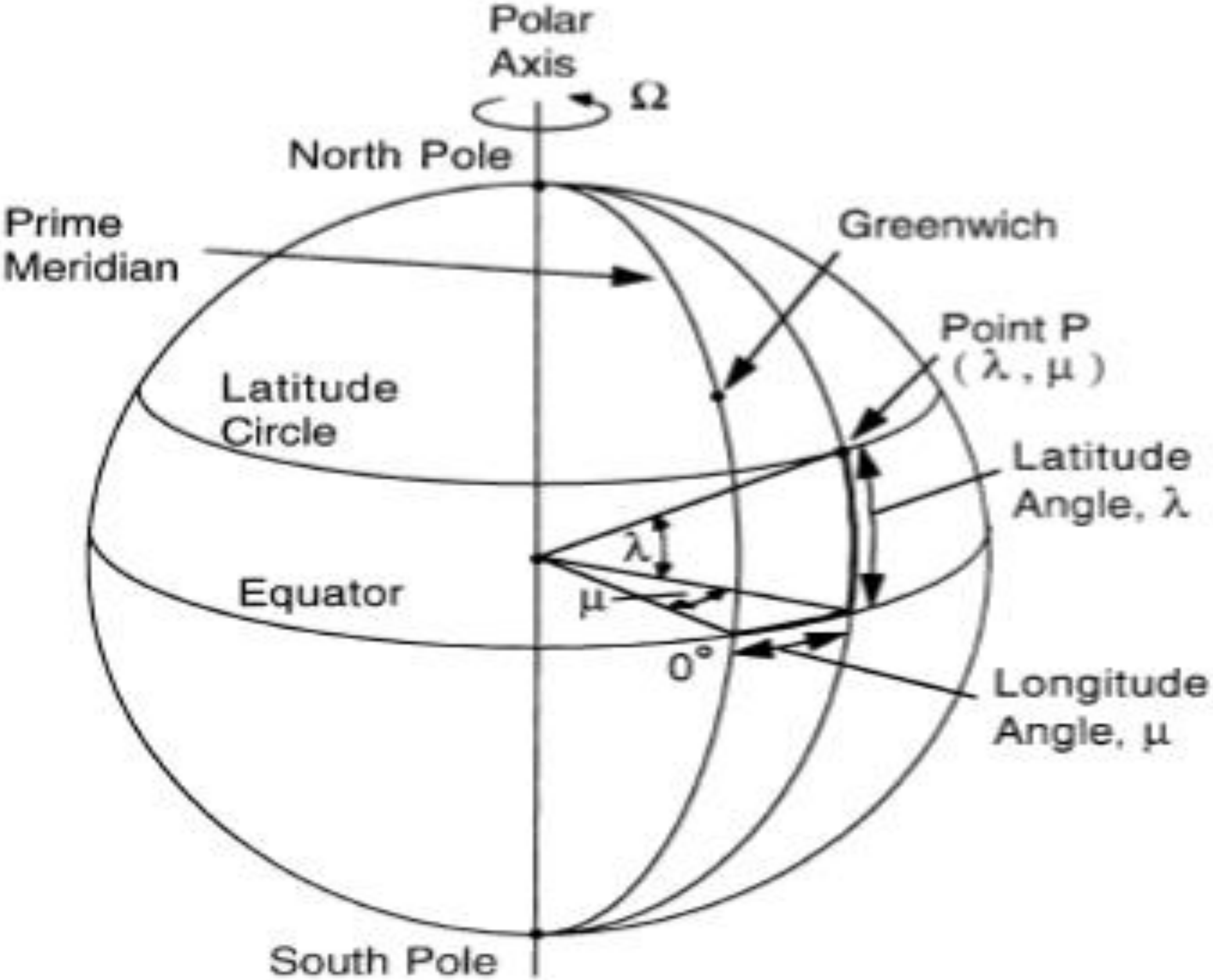

Fig. 6.2 Latitude/longitude co-ordinates.

Fig. 6.3 Spherical triangles.

6.1.3 Basic DR Navigation Systems

The basic principles of deriving a DR navigation position estimate are explained below. The following quantities are required:

1. Initial position – latitude/longitude.
2. The northerly and easterly velocity components of the aircraft, V_N and V_E.

Referring to Figure 6.4 it can be seen that the rate of change of latitude is

$$\dot{\lambda} = \frac{V_N}{R} \tag{6.1}$$

the rate of change of longitude is

$$\dot{\mu} = \frac{V_E}{R\cos\lambda}$$

i.e.

$$\dot{\mu} = \frac{V_E}{R}\sec\lambda \tag{6.2}$$

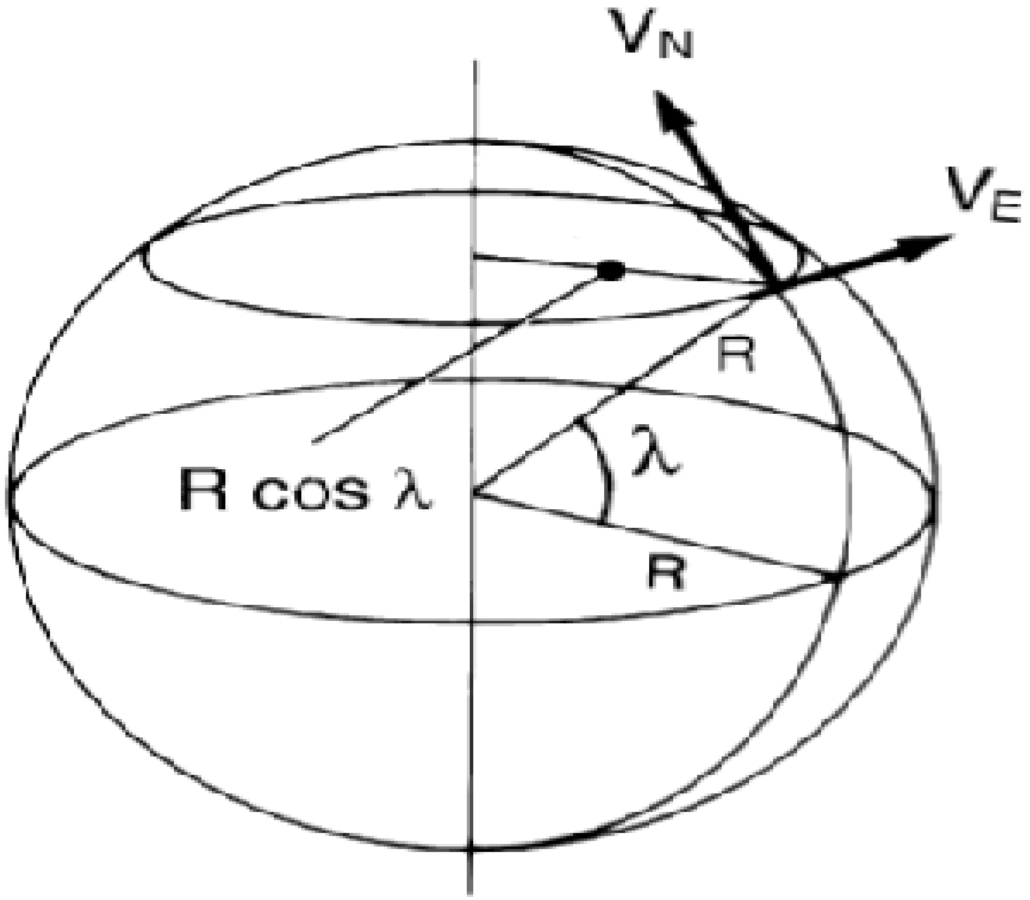

Fig. 6.4 Derivation of rates of change of latitude and longitude.

The change in latitude over time, t, is thus equal to $1/R \int_0^t V_N dt$ and hence the present latitude at time t can be computed given the initial latitude λ_0. Similarly, the change in longitude is equal to $1/R \int_0^t V_E \sec\lambda dt$ and hence the present longitude can be computed given the initial longitude, μ_0, viz.

can be computed given the initial longitude, μ_0, viz.

$$\lambda = \lambda_0 + \frac{1}{R}\int_0^t V_N dt \tag{6.3}$$

$$\mu = \mu_0 + \frac{1}{R}\int_0^t V_E \sec\lambda dt \tag{6.4}$$

It can be seen that a mathematical singularity is approached as λ approaches 90° and $\sec\lambda$ approaches infinity. This method of computing the latitude and longitude of the DR position is hence limited to latitudes below 80°. A different co-ordinate reference frame is used to deal with high latitudes as will be explained later.

The basic computational processes in a DR navigation system using a Doppler/heading reference system are shown in Figure 6.5. In the case of a Doppler/heading reference system, the ground speed V_G and drift angle δ are measured directly by the Doppler radar velocity sensor system.

The AHRS system provides an accurate measurement of the heading angle, ψ, and hence the track angle, ψ_T can be obtained from

$$\psi_T = \psi + \delta$$

The northerly velocity component of the aircraft, V_N, and the easterly velocity component, V_E, are then derived by resolution of the ground speed vector, V_G (see inset diagram on Figure 6.5).

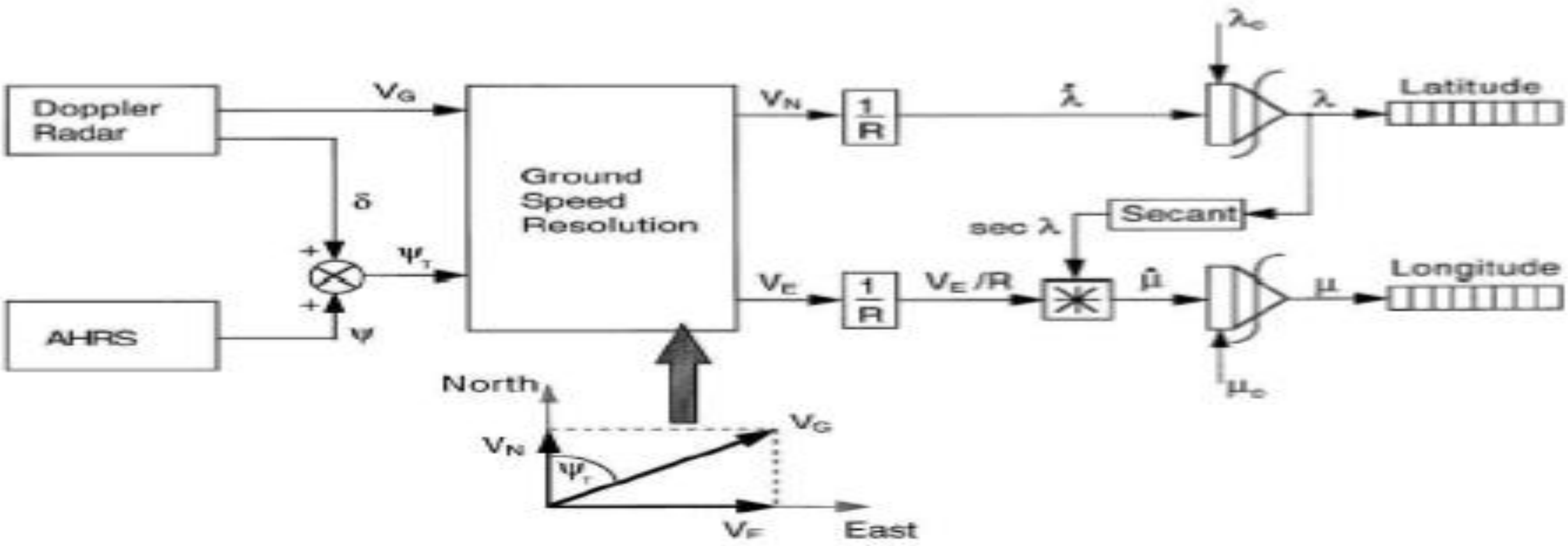

Fig. 6.5 Doppler/heading reference DR navigation system.

Hence

$$V_N = V_G \cos \psi_T$$
$$V_E = V_G \sin \psi_T$$

In the case of an air data based DR navigation system the northerly and easterly velocity components of the aircraft can be derived as follows:

1. The horizontal velocity component V_H of the true airspeed V_T is obtained by resolving V_T through the aircraft pitch angle θ, viz.

$$V_H = V_T \cos\theta$$

2. The northerly and easterly velocity components of the airspeed are then derived by resolving V_H through the aircraft heading angle ψ, viz.

$$\text{Northerly airspeed} = V_H \cos\psi$$

$$\text{Easterly airspeed} = V_H \sin\psi$$

3. The forecast (or estimated) wind speed V_W and direction ψ_W is resolved into its northerly and easterly components, viz.

$$\text{Northerly wind component} = V_W \cos\psi_W$$

$$\text{Easterly wind component} = V_W \sin\psi_W$$

4. The northerly and easterly velocity components of the aircraft are then given by:

$$V_N = V_H \cos \psi + V_W \cos \psi_W \tag{6.5}$$

$$V_E = V_H \sin \psi + V_W \sin \psi_W \tag{6.6}$$

Such a system provides a reversionary DR navigation system in the absence of Doppler (or an INS) and would generally be used in conjunction with a radio navigation system.

6.5 GPS – Global Positioning System

6.5.1 Introduction

GPS is basically a radio navigation system which derives the user's position from the radio signals transmitted from a number of orbiting satellites.

The fundamental difference between GPS and earlier radio navigation systems, such as LORAN-C (now no longer in use), is simply the geometry of propagation from ground based transmitters compared with space borne transmitters. An orbiting satellite transmitter can provide line of sight propagation over vast areas of the world. This avoids the inevitable trade-offs of less accuracy for greater range which are inherent with systems using ground based transmitters. The satellite signals also penetrate the ionosphere rather than being reflected by it so that the difficulties encountered with sky waves are avoided.

GPS provides a superior navigation capability to all previous radio navigation systems. For these reasons and also space constraints, coverage of radio navigation systems has been confined to GPS.

Satellite navigation can be said to have started with the successful launching by the Russians of the world's first orbiting satellite, SPUTNIK 1 in October 1957. The development of the first satellite navigation system TRANSIT 1, was triggered by observations made on the radio signals transmitted from SPUTNIK 1 and was

6.5.2 GPS System Description

The overall GPS system comprises three segments, namely the space segment, the control segment and the user segment and is shown schematically in Figure 6.30. The three segments are briefly summarised below.

Space Segment. This comprises 24 GPS satellites placed in six orbital planes at 55° to the equator in geo-synchronous orbits at 20,000 km above the Earth. The orbit tracks over the Earth, forming an ‘egg beater’ type pattern.

Twenty-one satellites are required for full worldwide coverage and three satellites act as orbiting spares.

The GPS satellites use two frequency transmissions, L1 at 1575.42 MHz and L2, at 1227.6 MHz for transmitting the digitally encoded navigation message data at 50 Hz modulation on both the L1 and L2 channels. The navigation message data will be explained in more detail in the next section but basically comprises the satellite orbital position parameters, clock correction parameters and health information for itself and the other satellites, and the almanac data for all the satellites.

Spread spectrum techniques are used on both the L1 and L2 frequency channels.

The L1 carrier is modulated by a 1.023 MHz clock rate pseudo-random code known as the Coarse/Acquisition (C/A) code; a different C/A code is assigned to each satellite. A quadrature carrier component of the L1 signal is modulated by the Precise (P) code which uses ten times the clock rate of the C/A code.

The L2 transmission is modulated by the P code only and enables corrections to be made for ionospheric delay uncertainties, the dual frequency transmission enabling these corrections to be derived.

It should be noted that, until fairly recently, the GPS accuracy available to civil users was deliberately degraded to 100 m. The full accuracy of 16 m could only be obtained by military users with access to the P code on the L2 transmission, which was encrypted. This restriction was removed in 2000.

Control Segment. This comprises a Master Control Station at Colorado Springs in the USA and five monitor stations located worldwide. The control segment is operated by the United States Department of Defense (DoD). The control segment tracks the satellites and predicts their future orbital position data and the required satellite clock correction parameters, and updates each satellite on the uplink as it goes overhead.

The GPS full system accuracy is only available when the operational control system is functioning properly and navigation messages are uploaded on a daily basis. The GPS satellites are, however, designed to function with the control system inoperable for a period of 180 days with gradually degraded accuracy. This gives the GPS system a high degree of robustness.

User Segment. The user segment equipment as mentioned earlier is entirely passive and comprises a GPS receiver. A very wide variety of compact, light weight and inexpensive GPS receivers are now available, all using the same basic concepts.

The user system operation is very briefly as follows. The operator first enters the estimated present position and the time. The GPS receiver then starts to search for and track satellites. The data coming in identifies the satellite number, locates the satellite in space and establishes the system time. As will be explained in the next section the GPS receiver needs to track the signals from at least four satellites to determine the user's position.

As mentioned in the introduction to this chapter, the user's 3D position is determined to an accuracy of 16 m RMS, 3D velocity to 0.1 m/s RMS by measuring the Doppler shifts, and time to within 100 ns (1 sigma).

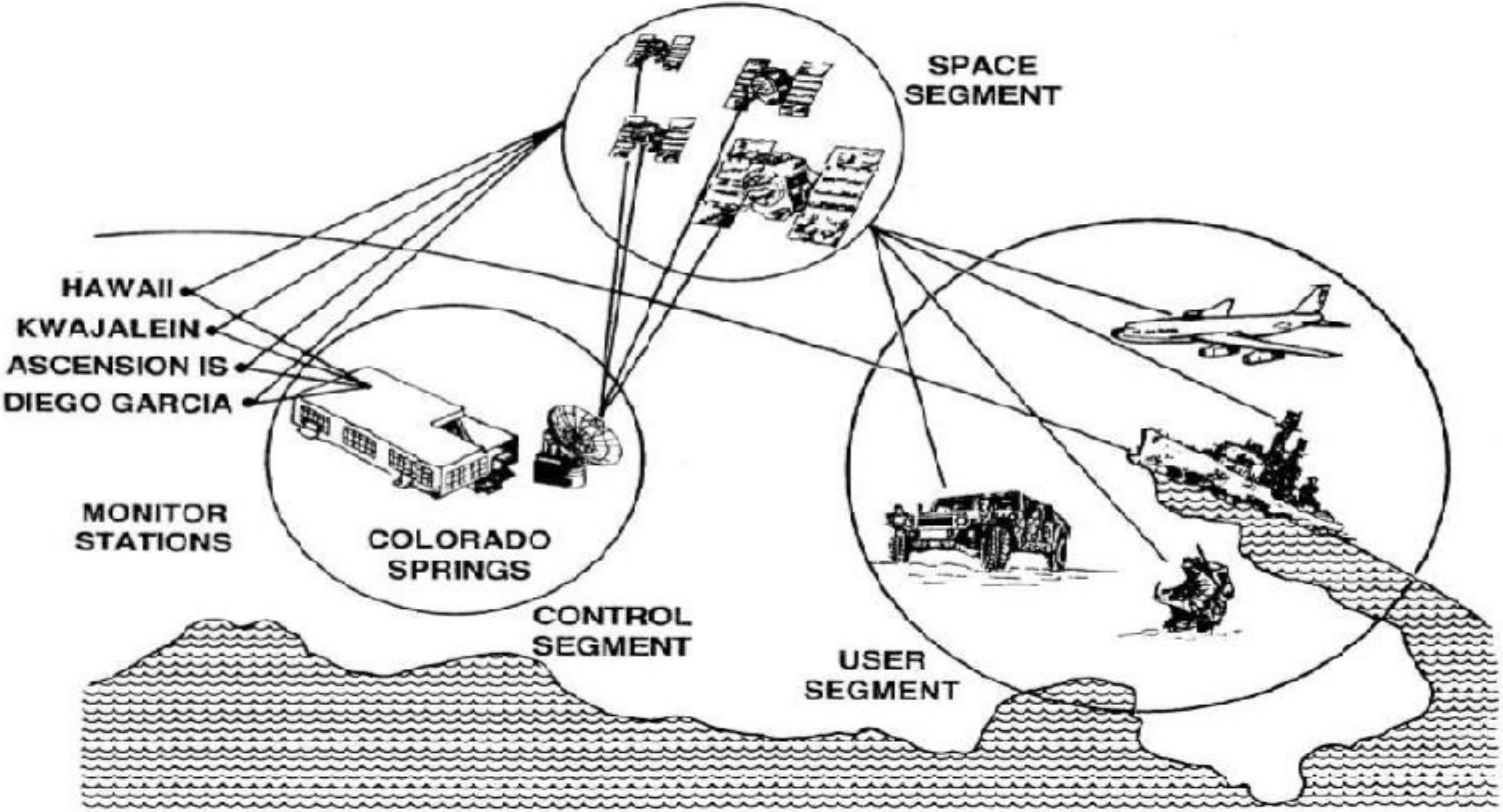

Fig. 6.30 The GPS system.

6.5.3 *Basic Principles of GPS*

The basic principle of position determination using the GPS system is to measure the spherical ranges of the user from a minimum of four GPS satellites. The orbital positions of these satellites relative to the Earth are known to extremely high accuracy and each satellite transmits its orbital position data.

Each satellite transmits a signal which is modulated with the C/A pseudo-random code in a manner which allows the time of transmission to be recovered.

The spherical range of the user from the individual transmitting satellite can be determined by measuring the time delay for the satellite transmission to reach the user. Multiplying the time delay by the velocity of light then gives the spherical range, *R*, of the user from the transmitting satellite. The user's position hence lies on the surface of a sphere of radius, *R*, as shown in Figure 6.31.

The system depends on precise time measurements and requires atomic clock reference standards. The need for extremely high accuracy in the time measurement can be seen from the fact that a 10 ns (10^{-8} seconds) time error results in a distance error of 3 metres, as the velocity of light is 3×10^8 m/s.

Each GPS satellite carries an atomic clock which provides the time reference for the satellite data transmission. Assume for the moment that this time is perfect – the corrections required will be explained shortly. Given a perfect time reference in the user equipment, measurement of the spherical ranges of three satellites would be sufficient to determine the user's position. The user's equipment, however, has a crystal clock time reference which introduces a time bias in the measurement of the transit times of the satellite transmissions. The measurement of the time delay is thus made up of two components. The first component is the transit time of the ranging signal and the second component is the time offset between the transmitter clock and the receiver clock due to the non-synchronisation of the clocks.

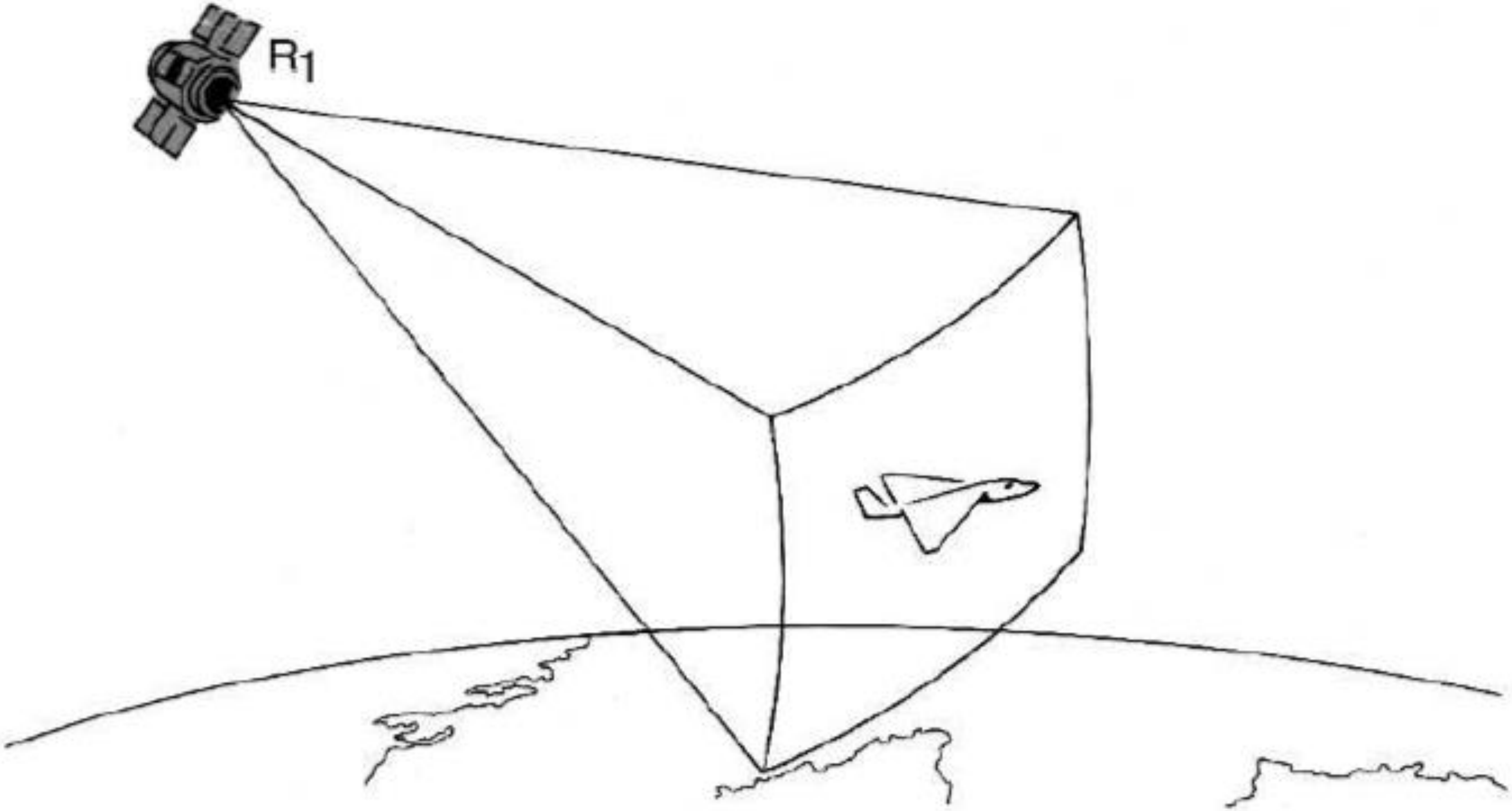

Fig. 6.31 GPS spherical ranging.

clock and the receiver clock due to the non-synchronisation of the clocks.

Measuring the spherical ranges from four satellites as shown in Figure 6.32 enables the user's position to be determined and yields four equations containing the four unknowns, viz the three position co-ordinates of the user and the time bias in the user's clock. The position co-ordinates of the user can thus be determined together with very accurate time information. Figure 6.33 shows the data transmission waveforms and illustrates the user time bias ΔT, and the time delays Δ_{t_1}, Δ_{t_2}, Δ_{t_3} and Δ_{t_4} for the signals transmitted from the satellites to reach the user.

Four pseudo ranges R_{1p}, R_{2p}, R_{3p}, R_{4p} to the four satellites S1, S2, S3, S4 can be determined, viz.

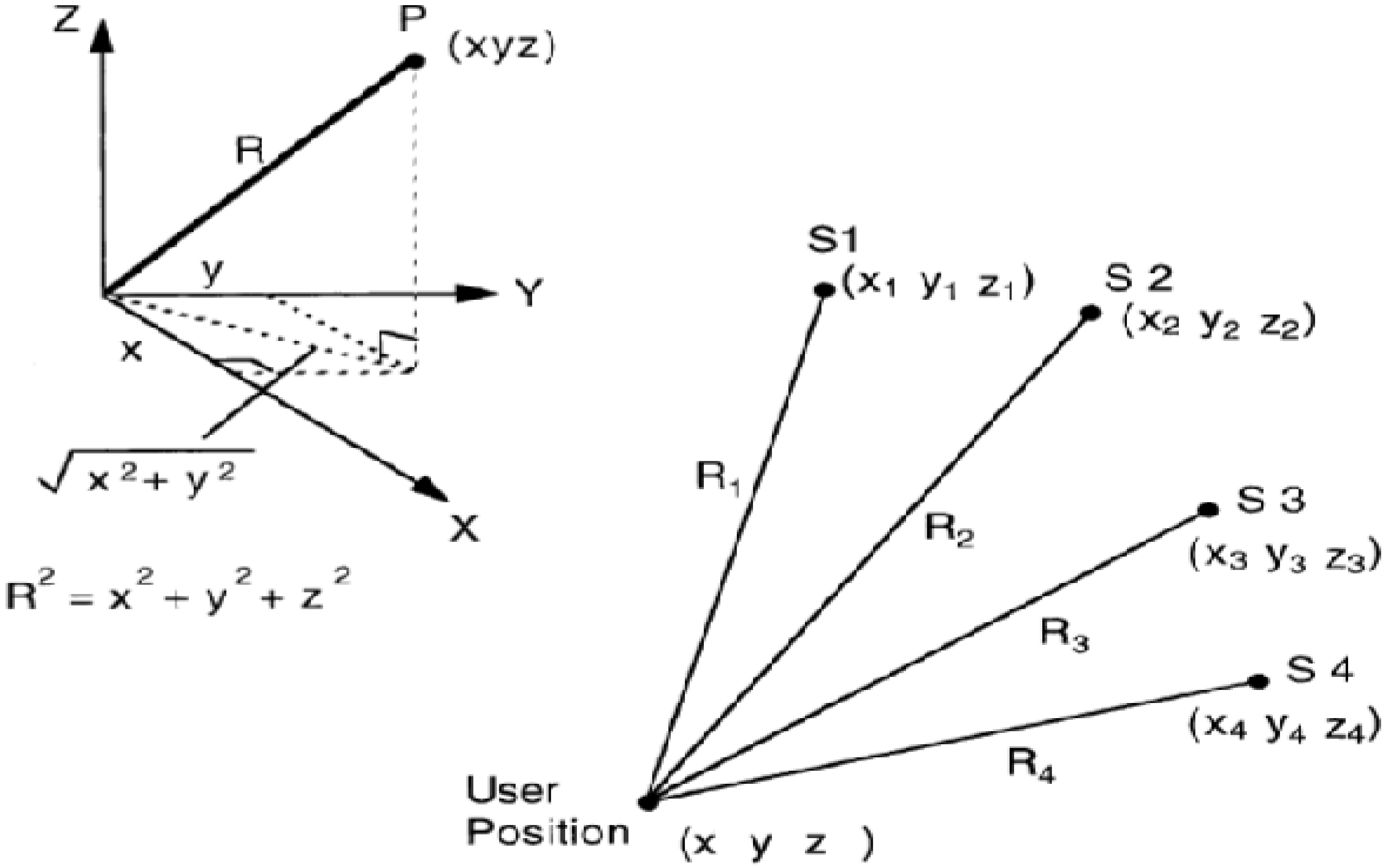

Fig. 6.32 User–satellite geometry.

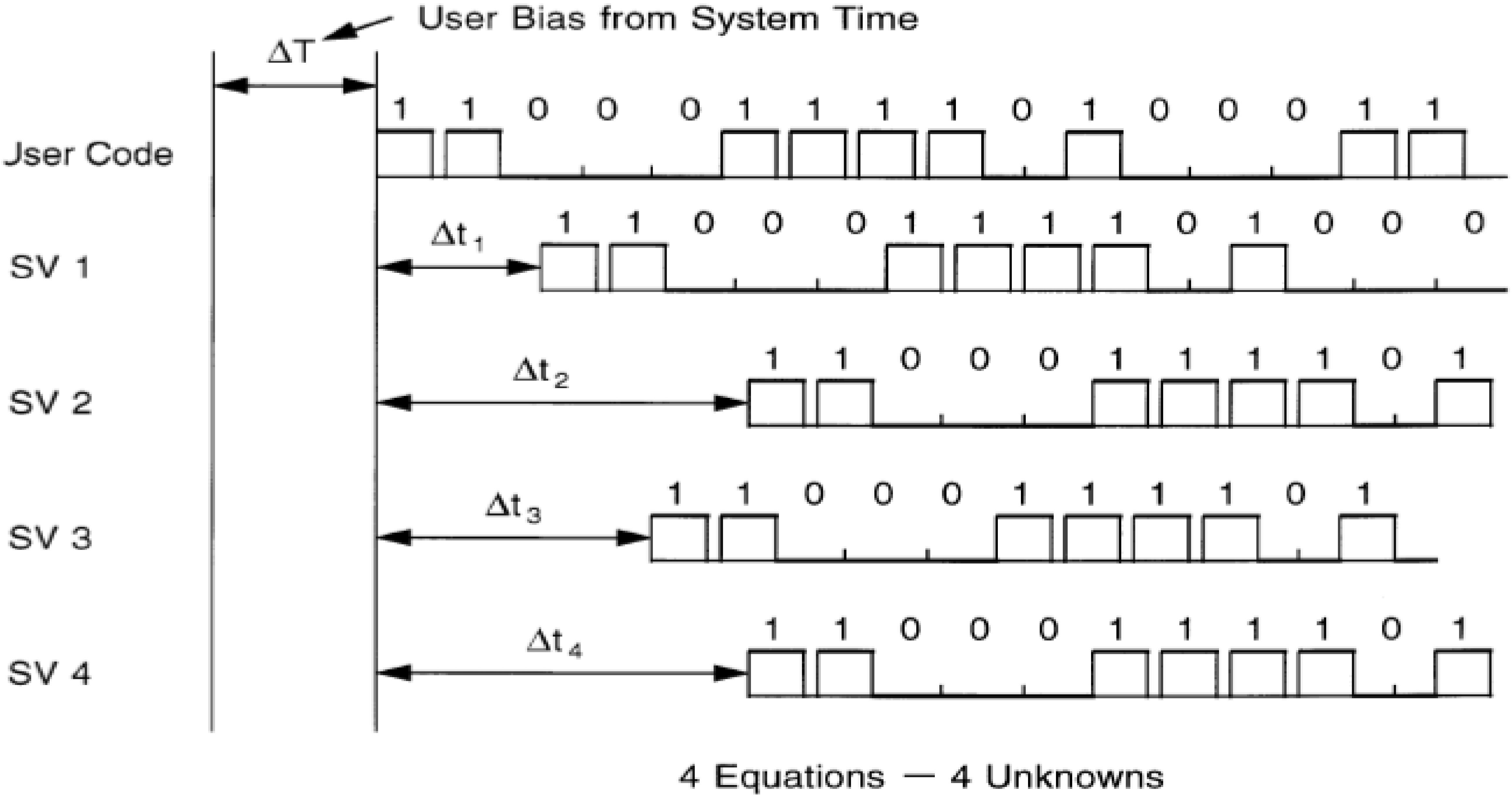

Fig. 6.33 GPS satellite waveforms with perfect satellite clocks.

$$
\begin{aligned}
R_{1p} &= c\Delta t_1 \\
R_{2p} &= c\Delta t_2 \\
R_{3p} &= c\Delta t_3 \\
R_{4p} &= c\Delta t_4
\end{aligned}
\tag{6.55}
$$

Let the range equivalent of the user's clock offset be T, i.e.

$$T = c_{\Delta}T$$

Hence, from basic 3D co-ordinate geometry (see Figure 6.31)

$$R_1 = [(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2]^{1/2} = R_{1p} - T \tag{6.56}$$

$$R_2 = [(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2]^{1/2} = R_{2p} - T \tag{6.57}$$

$$R_3 = [(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2]^{1/2} = R_{3p} - T \tag{6.58}$$

$$R_4 = [(X - X_4)^2 + (Y - Y_4)^2 + (Z - Z_4)^2]^{1/2} = R_{4p} - T \tag{6.59}$$

when R_1, R_2, R_3, R_4 are the actual ranges from the user's position to the four satellites S1, S2, S3, S4 and the coordinates of these satellites are $(X_1\ Y_1\ Z_1)$, $(X_2\ Y_2\ Z_2)$, $(X_3\ Y_3\ Z_3)$, $(X_4\ Y_4\ Z_4)$ respectively.

These four equations with four unknowns can thus be solved and yield the user's position coordinates (X, Y, Z) and the user's time offset, ΔT.

Each satellite time is related to GPS time by a mathematical expression and the user corrects the satellite time to the GPS time using the equation

$$t = t_{s/c} - \Delta t_{s/c} \tag{6.60}$$

where t is the GPS time in seconds, $t_{s/c}$ is the effective satellite time at signal transmission in seconds and $\Delta t_{s/c}$ is the time offset between the satellite and GPS master time.

The time offset is $\Delta t_{s/c}$ computed from the following equation

$$\Delta t_{s/c} = a_0 + a_1(t - t_{o/c}) + a_2(t - t_{o/c})2 + \Delta t_r \tag{6.61}$$

where a_0, a_1, and a_2 are polynomial coefficients representing the phase offset, frequency offset and ageing term of the satellite clock with respect to the GPS master time and Δt_r is the relativistic term (seconds). The parameter t is the GPS time and $t_{o/c}$ is the *epoch time* at which the polynomial coefficients are referenced and generally $t_{o/c}$ is chosen at the mid point of the fit interval. The polynomial coefficients a_0, a_1, a_2 are estimated by the control segment for each satellite clock and periodically uplinked to the satellite.

These coefficients are transmitted together with the satellite orbital position data, termed the *Ephemeris parameters*, to the navigation user equipment as navigation messages. The clock corrections for the four satellites are designated τ_1, τ_2, τ_3, and τ_4.

The spherical ranges R_1, R_2, R_3 and R_4 are thus given by

$$\begin{aligned}
R_1 &= c(\Delta t_1 + \Delta T - \tau_1) \\
R_2 &= c(\Delta t_2 + \Delta T - \tau_2) \\
R_3 &= c(\Delta t_3 + \Delta T - \tau_3) \\
R_4 &= c(\Delta t_4 + \Delta T - \tau_4)
\end{aligned} \tag{6.62}$$

All satellite clocks are mathematically synchronised to the GPS master time by means of these clock correction terms. The error in synchronisation will grow, however, if the polynomial coefficients a_0, a_1 and a_2 are not updated periodically.

The navigation user requires the Ephemeris parameters, that is the instantaneous position data of the GPS satellites which are being used for range measurement, as well as the clock parameters in order to compute the users position. The Ephemeris parameters defining the satellite orbital position data with respect to Earth reference axes comprise 16 parameters in all. Figure 6.34 illustrates the satellite–Earth geometry and the definition of the orbit parameters. The control segment processes the tracking data acquired from the monitor stations to generate the orbit estimates for the GPS satellites. The predicted estimates of the satellite position co-ordinates are generated by integrating the equations of motion of the GPS satellites. These Cartesian position co-ordinates are then fitted mathematically over a specified interval of time to compute the Ephemeris parameters.

Both clock and Ephemeris parameters are down linked to the user at 50 bits per second data rate modulated in both C/A and P code (Y code) navigation signals. The navigation message uses a basic format consisting of a 1500 bit long frame made up of five sub-frames, each sub-frame being 300 bits long. Sub-frames 4 and 5 are sub-commuted 25 times each so that a compete data message takes a transmission of 25 full frames. Sub-frame 1 contains the clock parameters and sub-frames 2 and 3 the Ephemeris parameters for the satellite. Sub-frames 1, 2 and 3 are repeated every 30 seconds so that it is possible for the user to update the clock and Ephemeris parameters every 30 seconds. Sub-frames 4 and 5 have each 25 pages so that these sub-frames are repeated only once in 12.5 minutes.

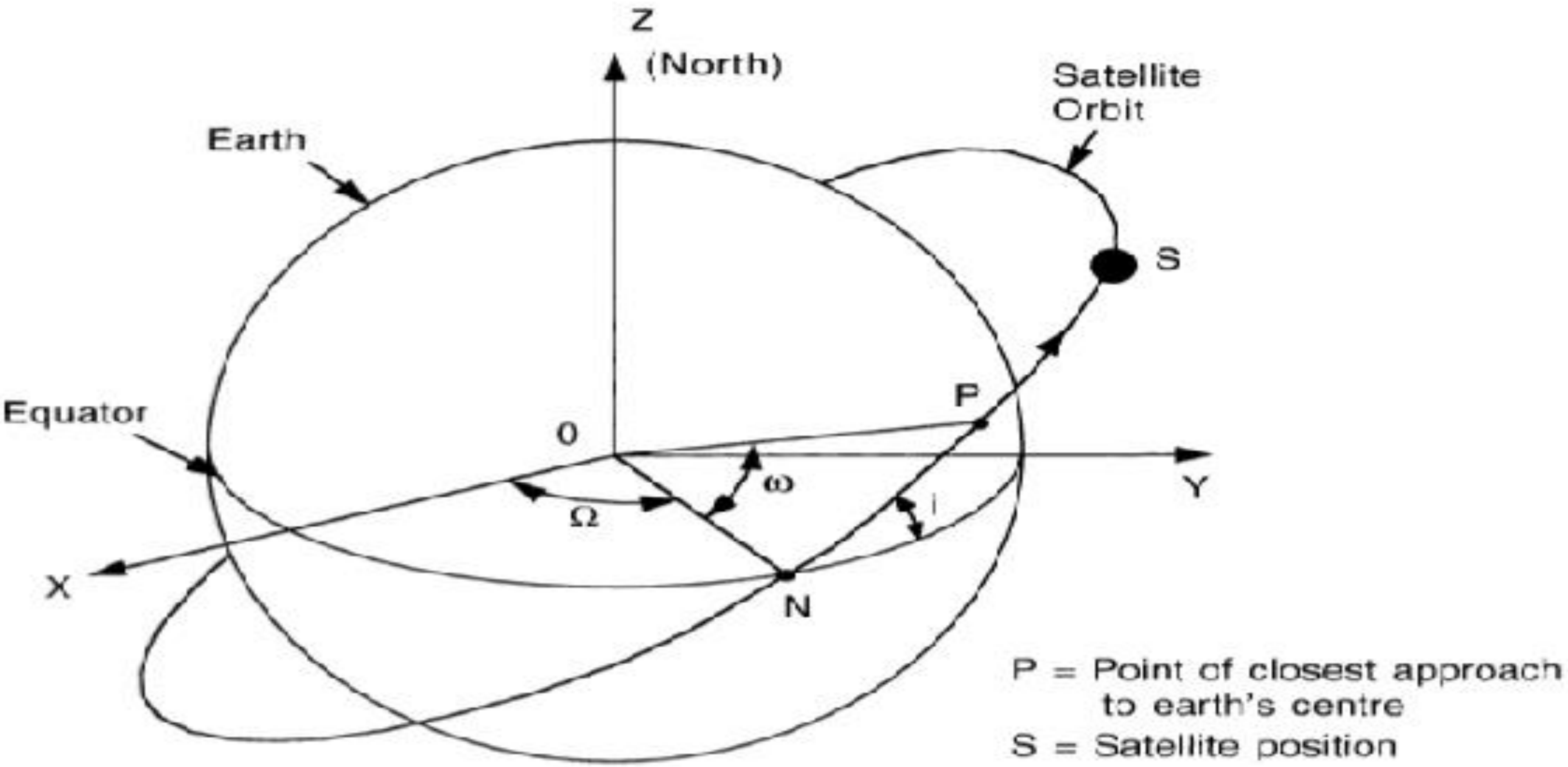

Fig. 6.34 Satellite-Earth geometry. Ephemeris parameter definition.

The navigation equations are basically non-linear as can be seen in equations (6.56), (6.57), (6.58) and (6.59), but can be linearised about nominal values for their solution by applying Taylor's series approximations.

6.5.5 Integration of GPS and INS

GPS and INS are wholly complementary and their information can be combined to the mutual benefit of both systems. For example:

- Calibration and correction of INS errors – the GPS enables very accurate calibration and correction of the INS errors in flight by means of a Kalman filter.
- The INS can smooth out the step change in the GPS position output which can occur when switching to another satellite because of the change in inherent errors.
- Jamming resistance – like any radio system, GPS can be jammed, albeit over a local area, although it can be given a high degree of resistance to jamming. The INS, having had its errors previously corrected by the Kalman filter, is able to provide accurate navigation information when the aircraft is flying over areas subjected to severe jamming.
- Antenna obscuration – GPS is a line of sight system and it is possible for the GPS antenna to be obstructed by the terrain or aircraft structure during manoeuvres.
- Antenna location corrections – the GPS derived position is valid at the antenna and needs to be corrected for reference to the INS location. The INS provides attitude information which together with the lever arm constants enables this correction to be made.

6.5.6 Differential GPS

6.5.6.1 Introduction

As explained in the preceding section the horizontal position accuracy available to all GPS users (civil and military) is now 16 m. This was not the case, however, until 2000 when the restriction of 'Selective Availability' was removed.

Concerns about potential enemies using GPS to deliver missiles and other weapons against the US had led to a policy of accuracy denial, generally known as Selective Availability. The GPS ground stations deliberately introduced satellite timing errors to reduce the positioning accuracy available to civil users to a horizontal positioning accuracy of 100 m to a 95% probability level. This was deemed adequate for general navigation use, but in practice it did not satisfy the accuracy or integrity requirements for land or hydrographic surveying, coastal navigation or airborne navigation. It should be noted that even the 16 m accuracy, now available, is insufficiently accurate for many applications. For example, positioning of off-shore oil drilling rigs or automatic landing in the case of airborne applications.

A supplementary navigation method known as *Differential GPS* (DGPS) has therefore been developed to improve the positioning accuracy for the growing number of civil applications.

DGPS can be defined as:

> The positioning of a mobile station in real-time by corrected (and possibly Doppler or phase smoothed) GPS pseudo ranges. The corrections are determined at a static ‘reference station’ and transmitted to the mobile station. A monitor station may be part of the system, as a quality check on the reference station transmissions.

The success of DGPS can be seen from its application to new markets such as locating land vehicles used by the emergency services. Successful trials for automatic landings and taxi-way guidance have also been conducted. It is now widely used in land and hydrographic surveying applications.

6.5.6.2 Basic Principles

The basic principle underlying DGPS is the fact that the errors experienced by two receivers simultaneously tracking a satellite at two locations fairly close to each other will largely be common to both receivers.

The basic differential GPS concept is illustrated in Figure 6.35. The position of the stationary GPS Reference Station is known to very high accuracy so that the satellite ranges can be very accurately determined, knowing the satellite ephemeris

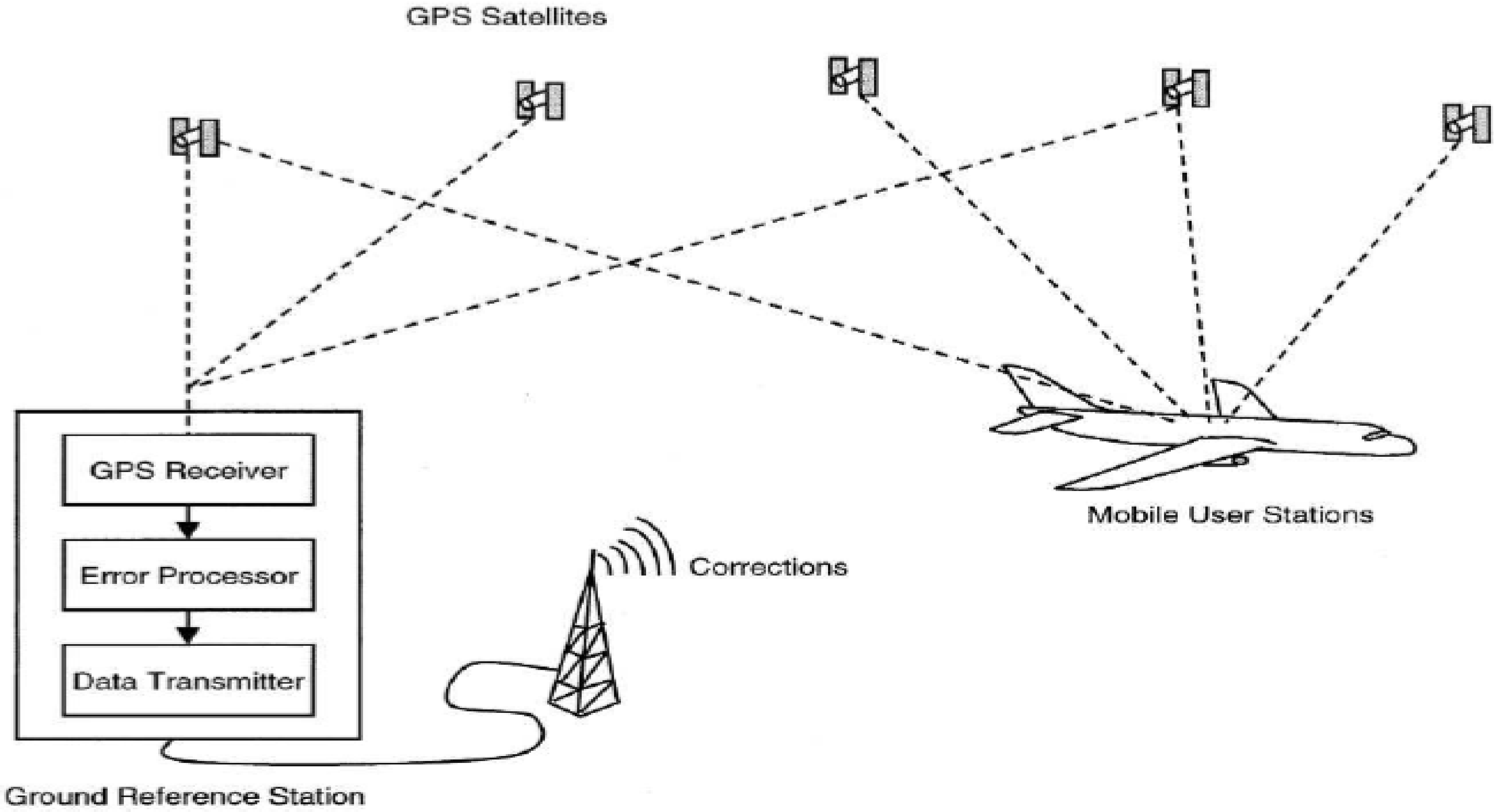

Fig. 6.35 The differential GPS concept.

data. The errors in the pseudo-range measurements can then be derived and the required corrections computed and transmitted to the user's receiver over a radio link. The errors present in a GPS system are illustrated schematically in Figure 6.36 and are briefly discussed below.

GPS satellite clocks. GPS satellites are equipped with very accurate atomic clocks and corrections are made via the Ground Stations, as explained in the preceding section. Even so, very small timing errors are present and so contribute to the overall position uncertainty.

Selective Availability deliberately introduced noise equivalent to around 30 m in the individual satellite clock signals.

Satellite ephemeris errors. The satellite position is the starting point for all the positioning computations, so that errors in the Ephemeris data directly affect the system accuracy. GPS satellites are injected into very high orbits and so are relatively free from the perturbing effects of the Earth's upper atmosphere. Even so, they still drift slightly from their predicted orbits and so contribute to the system error.

Atmospheric errors. Radio waves slow down slightly from the speed of light in vacuo as they travel through the ionosphere and the Earth's atmosphere. This is due respectively to the charged particles in the ionosphere and the water vapour and neutral gases present in the troposphere. These delays translate directly into a position error.

The use of different frequencies in the L1 and L2 transmissions enables a significant correction to be made for ionospheric delays. (It should be appreciated that this facility was not available to civil users prior to 2000.)

Table 6.3 Summary of GPS error sources.

Typical error budget (in metres)		
Per satellite accuracy	Standard GPS	Differential GPS
Satellite clocks	1.5	0
Orbit errors	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Selective availability*	30.0	0
Receiver noise	0.3	0.3
Multi-path (reflections)	0.6	0.6
Typical positioning accuracy		
Horizontal	50.0	1.3
Vertical	78.0	2.0
3D	93.0	2.8

**Note*: Selective Availability error is shown to demonstrate the effectiveness of the DGPS technique, although the Selective Availability restriction has now been removed.

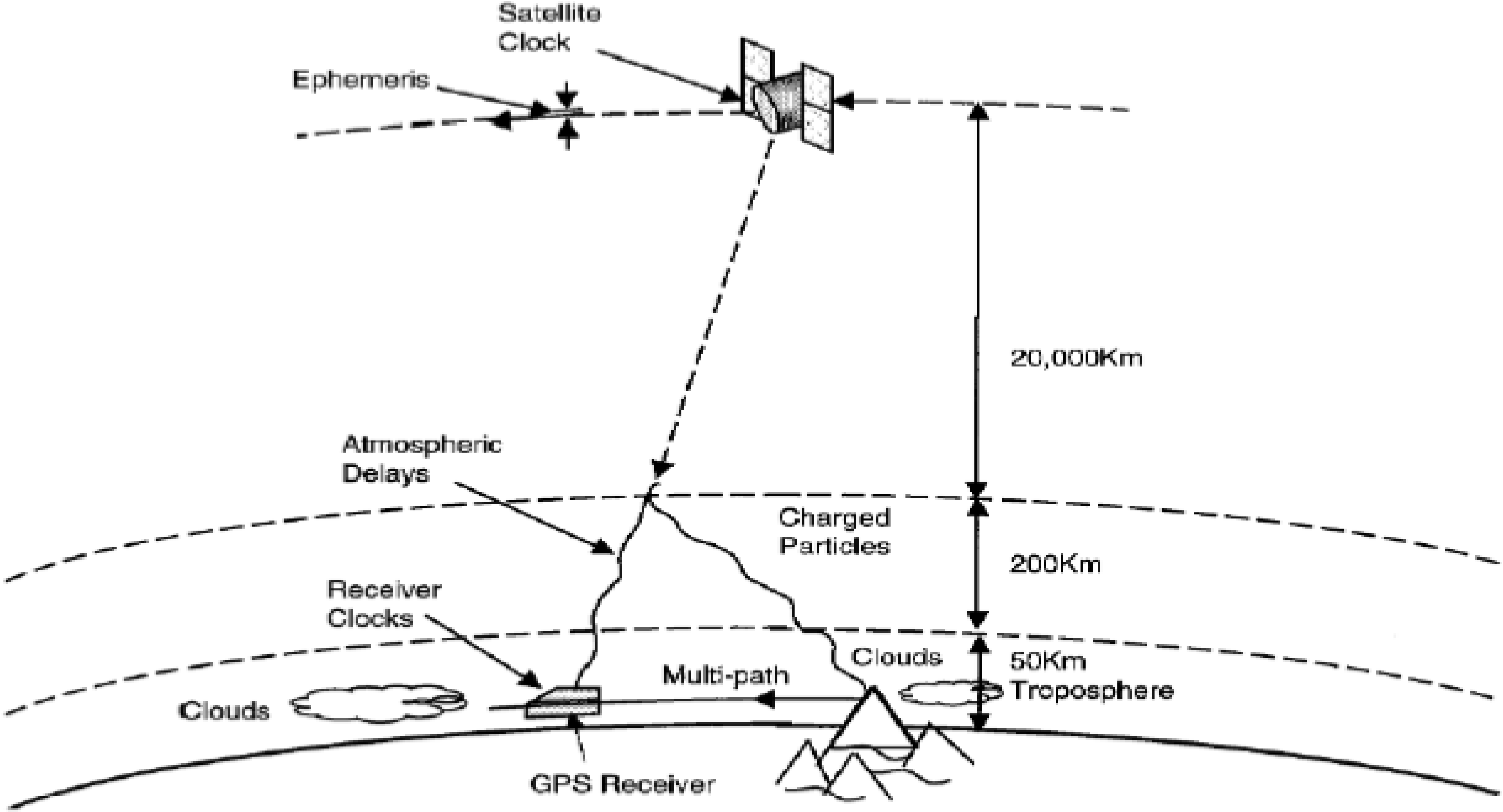

Fig. 6.36 GPS error sources.

Separation distances between the Ground Reference Station and the mobile user can be up to 300–500 km and separations of 1000 km or beyond are not unknown.

Figure 6.37 is a simplified functional diagram of a generic differential GPS system.

Radio links can be realised in one of a number of forms to provide a suitable narrow band communication channel to the mobile receiver. Dedicated radio channels within the MF, HF, VHF or UHF bands are used. Frequency diversity and error checking codes are used to provide protection against data corruption caused by the vagaries of propogation.

The satellite pseudo-range measurement in the user's GPS receiver is carried out by the correlation of the received satellite signal with the receiver generated replica of the known satellite C/A code using a code tracking loop. The accuracy of the time measurement by the C/A code tracking loop is inevitably ultimately limited by noise sources such as multi-path reception.

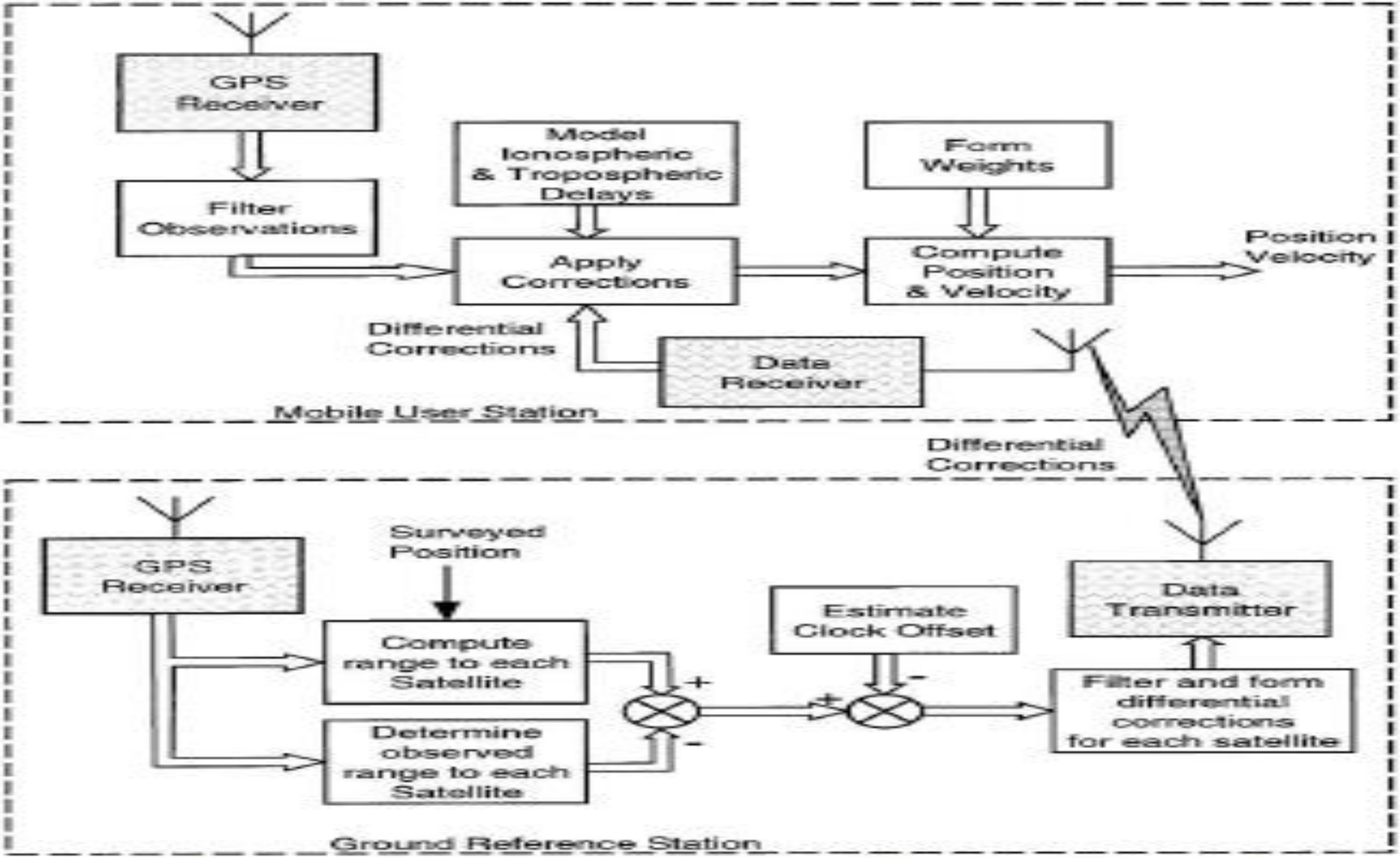

Fig. 6.37 Simplified functional diagram of a generic differential GPS system.

GPS receivers also employ carrier tracking loops to monitor the Doppler shifted carrier component of the satellite navigation signals. The Doppler shift is proportional to the radial velocity of the receiver relative to the satellite. The velocity of the user vehicle is computed from these Doppler shifts.

The Ground Reference GPS Station in the DGPS system uses these Doppler frequency shift measurements to improve the accuracy of the pseudo-range measurements. Integrating the Doppler shift over an interval provides a measurement of the change in satellite-to-receiver range. The range itself cannot be measured because the integer number of carrier cycles is not known. The information extracted from a carrier tracking loop can take the form of a Doppler observation or a continuously integrated Doppler observation more commonly called a *carrier phase* observation. The multi-path and noise induced errors found in carrier phase observations are negligible compared to those on C/A code observations. The accuracy improvement is commensurate with the rates of the L1 code wavelength and carrier wavelength, 290 m and 0.19 m respectively. Carrier phase filtering can be carried out using Kalman filtering techniques.

6.5.7 Future Augmented Satellite Navigation Systems

The advent of satellite navigation systems and satellite communication links has provided new capabilities for aircraft precision navigation, particularly in civil operations.

Providing the integrity and accuracy requirements can be met, satellite navigation systems are able to support all phases of flight including all-weather precision approaches to airports not equipped with ILS (or MLS) installations.

In conjunction with satellite communication links, they can also proved the capability for remote air traffic control as shown in Figure 6.38.

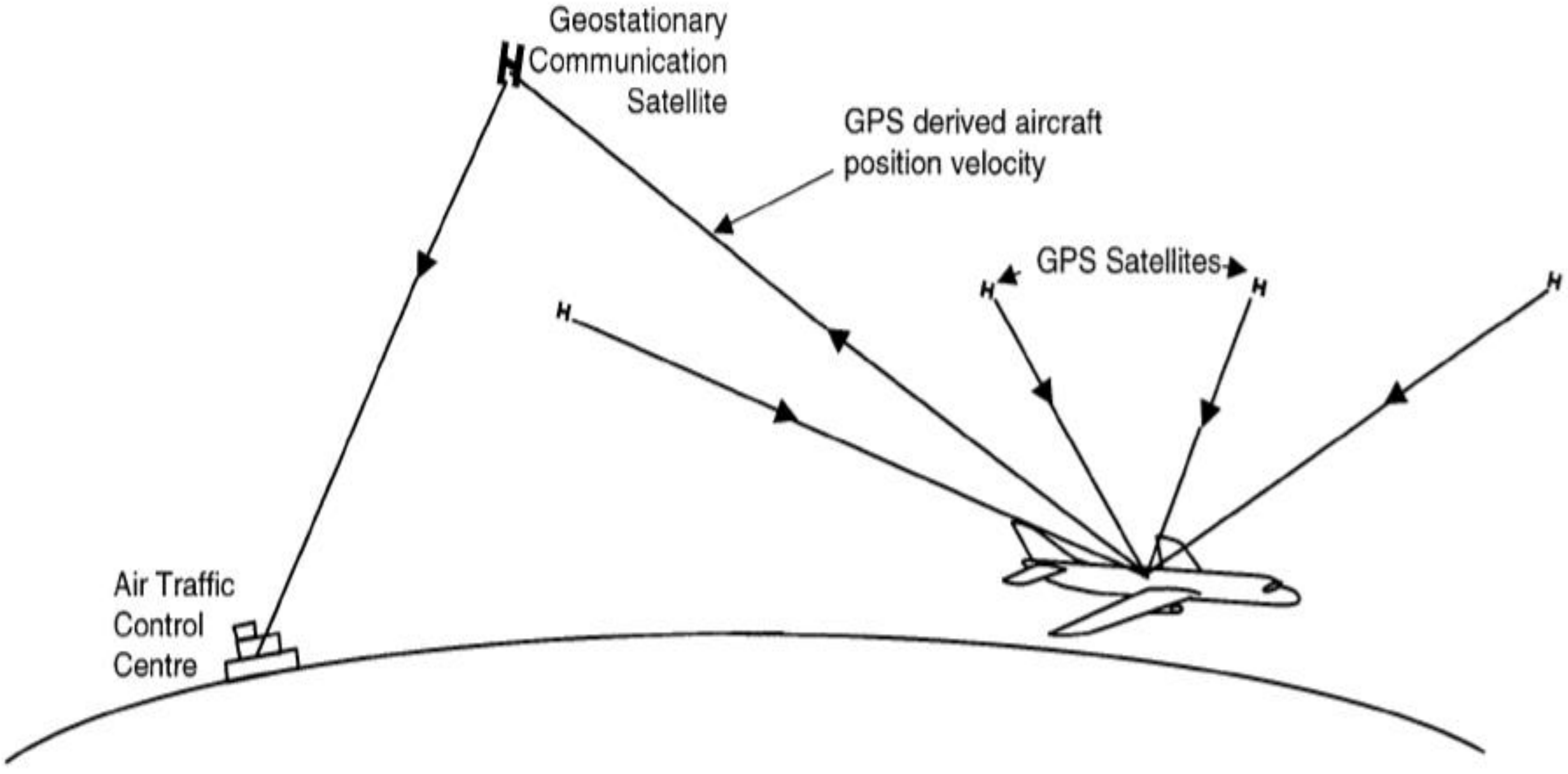

Fig. 6.38 Remote air traffic control.

An augmented satellite navigation system provided by additional satellites under international civil control was therefore proposed and studied in detail by the European civil authorities from the late 1990s. The additional ranging signals and monitoring will enable the integrity requirements to be met and will also provide increased accuracy.

The go-ahead for the new system, known as the Galileo system, was announced by the participating countries in the European Union in March 2002. The Galileo system will be inter-operable with GPS from a user perspective and will comprise up to 40 orbiting satellites. The system will provide a positional accuracy of the order of 1 metre worldwide when it comes into operation. The Galileo satellite navigation system is scheduled to enter service around 2014.

The development of differential GPS has enabled Ground Reference Stations to monitor the quality of the satellite transmissions. They provide an additional check on the GPS system integrity for users within a 500 to 1000 mile radius of these stations and enable differential corrections to be transmitted to these users. Increased accuracy is obtained with errors in the few metre bracket, depending on the range from the Ground Station (as explained in the preceding section).

A GPS satellite augmentation system is being developed in the USA under the auspices of the FAA called the Wide Area Augmentation System, WAAS.

The WAAS system is shown in Figure 6.39. This will provide increased integrity by monitoring the GPS satellite transmissions from a network of monitor ground stations in the US and increase the system accuracy by transmitting the differential corrections over communication satellite radio links. User position accuracy should be within 3 metres enabling precision approaches to be accomplished in Cat 2 visibility conditions.

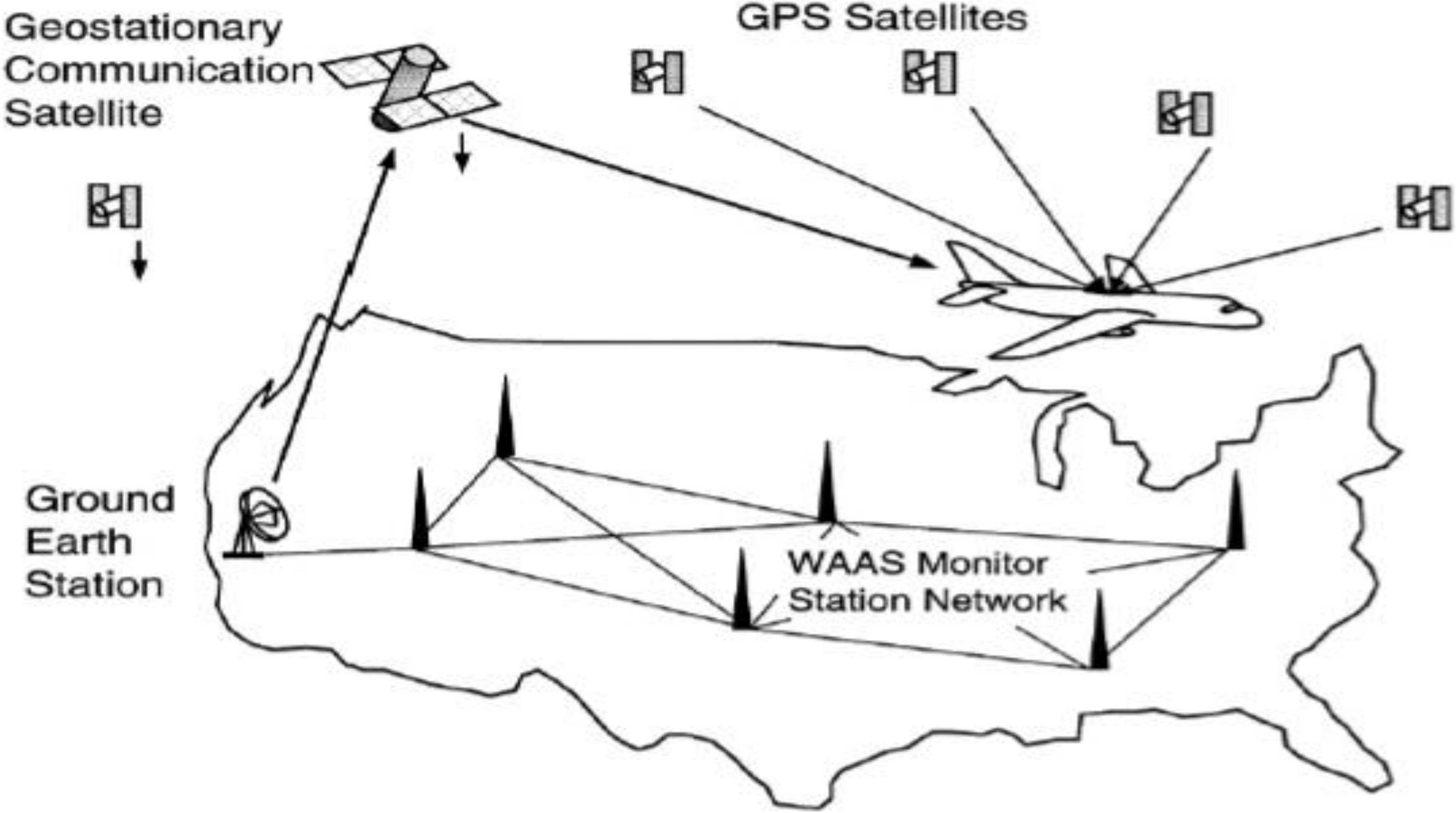

Fig. 6.39 Wide area augmentation system, WAAS, concept.

6.6 Terrain Reference Navigation

6.6.1 Introduction

Terrain reference navigation (TRN) is a generic classification which covers any technique of aided navigation which relies on correlating terrain measurement data from a suitable terrain sensor (or sensors) with the data stored in a digital map data base. The system is operated in conjunction with a DR navigation system; the position fixes derived by the TRN system are then used to update and correct the DR system errors by means of a Kalman filter. TRN systems can only be used over land and require a very accurate data base. The latter may need to be derived from satellite data when accurate map data are not available. Terrain reference navigation systems can be divided into three basic types:

1. *Terrain contour navigation (TCN)*. In this system, the terrain profile is measured by a radio altimeter and is matched with the stored terrain profile in the vicinity of the aircraft's position as previously estimated by the DR system.

2. *Terrain characteristic matching (TCM)*. This type of system can use a variety of sensors – e.g., radar or radiometric sensors to sense changes in the terrain characteristics below the aircraft. For example, flying over lakes, rivers, roads, woods, buildings etc. The data can then be processed to detect the edges or boundaries where the terrain characteristics change abruptly. The detected edges of the overflown features can then be matched with the stored terrain features in the vicinity of the aircraft's estimated position.

   Both TCN and TCM can be used in a complementary manner, TCN providing very good positional fixes where there are reasonable terrain contour variations. Over very flat terrain the TCN accuracy is degraded; however, the TCM system can then provide very good positional fixes from the detected edges of specific terrain features.
3. *Scene matching area correlation (SMAC)*. This is also known as digital scene matching area correlation (DSMAC) in the USA. These systems generally use an infrared imaging sensor to locate and lock on to specific recognisable landmarks or set of features at known positions on the route. An area correlation technique is used to match the processed image data with the stored feature data so that the system will track and lock on to the feature. The aircraft position must be known fairly accurately in the first place using, say, TCN.

The order of magnitude accuracies which can be achieved with these systems are:

TCN	around 50 metres
TCM	around 10 to 20 metres
SMAC	around 1 to 2 metres

6.6.2 Terrain Contour Navigation

The basic concepts of terrain contour navigation are illustrated in Figure 6.40. Three types of measurement data are required by the system:

1. A sequence of measurements of the ground clearance (i.e. height above ground level) of the aircraft. This is normally obtained by sampling the output of a radio altimeter, possibly with some additional pre-filtering. A horizontal sampling interval of about 100 metres is typically used, but this is not critical.
2. Data from a barometric or baro-inertial height system is required to measure any vertical motion of the aircraft between successive ground clearance measurements.

3. Some form of DR navigation system, eg an INS or Doppler radar plus heading reference is required to measure the relative horizontal positions of the ground clearance measurements.

The essence of TCN is to use this data to reconstruct the terrain profile under the aircraft's track. A digital map of terrain height is then searched to find a matching profile in the vicinity of the aircraft's position as previously estimated. This can then be used as the basis of an update to the estimated position.

There are a considerable number of TCN implementations which have been developed in the US and Europe to provide very accurate navigation systems such as TERCOM, TERPAC, SITAN, CAROTE, TERPROM, SPARTAN. Space constraints limit further coverage and the reader is referred to a number of papers which have been published on TRN systems in the Further Reading.

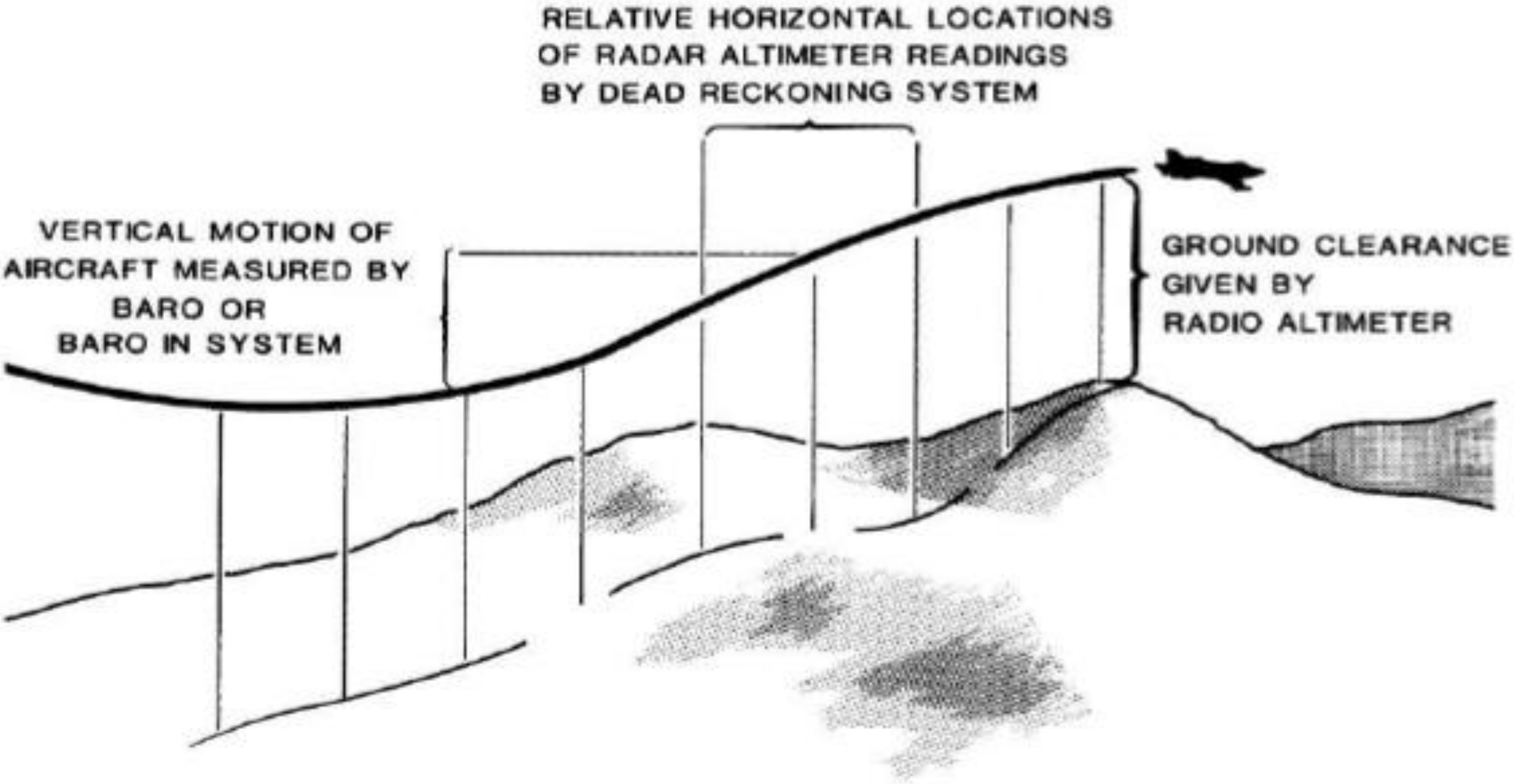

Fig. 6.40 Terrain reference system.


Thank You!