Global Positioning System (GPS)

Chris Rizos

Jiaozuo Institute of Technology

2003. 8

Chapter 7

Introducing the Global Positioning System

Chris Rizos

The NAVSTAR Global Positioning System (GPS) is a satellite-based radio-positioning and time-transfer system designed, financed, deployed, and operated by the US Department of Defense. GPS has also demonstrated a significant benefit to the civilian community, who are applying GPS to a rapidly expanding number of applications. The attractions of GPS are:

- Relatively high positioning accuracy, from meters down to the millimeter level.
- Capability of determining velocity and time, to an accuracy commensurate with position.
- No inter-station visibility is required for high precision positioning.
- Results are obtained with reference to a single, global datum.
- Signals are available to users anywhere on the earth: in the air, on the ground, or at sea.
- No user charges, requiring only relatively low-cost hardware.
- An all-weather system, available 24 hours a day.
- Position information is provided in three-dimensions.

Since its introduction to the civilian community in the early 1980s GPS has revolutionized geodesy, surveying and mapping. Indeed, the first users were geodetic surveyors, who applied GPS to the task of surveying the primary control networks that form the basis of all map data and digital databases. Today, around the world, GPS is the preferred technology for this geodetic application. However, as a result of progressive product innovations, the GPS technology is increasingly addressing the precise positioning needs of cadastral, engineering, environmental, planning and Geographical Information System (GIS) surveys, as well as a range of new machine, aircraft and ship location applications.

7.1. Background

Development work on GPS commenced within the US Department of Defense in 1973. The objective was to design and deploy an all-weather, 24 hour, global, satellite-based navigation system to support the positioning requirements of the US armed forces and its allies. For a background to the development of the GPS system the reader is referred to Parkinson (1994). GPS was intended to replace the large number of navigational systems already in use, and great importance was placed on the system's reliability and survivability. Therefore a number of stringent conditions had to be met:

- Suitable for all military platforms: aircraft (jet to helicopter), ships, land (vehicle-mounted to handheld) and space-based vehicles (missiles and satellites);
- Able to handle a wide variety of platform dynamics;
- A real-time positioning, velocity and time determination capability to an appropriate accuracy;
- The positioning results were to be available on a single, global, geodetic datum;
- The highest accuracy was to be restricted to the military user;
- Resistant to jamming (intentional and unintentional);
- Incorporating redundancy mechanisms to ensure the survivability of the system;
- A passive positioning system that did not require transmission of signals by the user;
- Able to provide the positioning service to an unlimited number of users;
- Use low-cost, low-power user hardware, and
- Was to be a replacement for the Transit satellite system, as well as other terrestrial navigation systems.

What was unforeseen by the system designers was the power of commercial product innovation, which has added significantly to the versatility of GPS, but in particular as a system for *precise positioning*. For example, GPS is able to support a variety of positioning and measurement modes in order to simultaneously satisfy a wide range of users; from those satisfied with navigational accuracy (of the order of 10 m), to those demanding very high (even sub-centimeter) positioning accuracy. *GPS has now so penetrated certain application areas so that it is difficult to imagine life without it!* Part 2 of this manual is not intended to be a comprehensive textbook on the GPS technology and its applications. Excellent general references to the engineering aspects of GPS are Kaplan (1996) and Parkinson and Spilker (1996). Texts dealing exclusively with the high precision GPS surveying techniques include Leick (1995), Hofmann-Wellenhof *et al.* (1998), and Teunissen and Kleusberg (1998).

A discussion of the GPS technology and applications starts with the identification of the three components (Figure 7.1).

- *The space segment:* the satellites and the transmitted signals.
- *The control segment:* the ground facilities carrying out the task of satellite tracking, orbit computations, telemetry and supervision necessary for routine operations.
- *The user segment:* the applications, equipment and computational techniques that are available to the users.

7.1.1. The space segment

The space segment consists of the constellation of spacecraft, and the signals that are broadcast by them, which allow users to determine position, velocity and time. The basic functions of the satellites are to:

- Receive and store data uploaded by the control segment

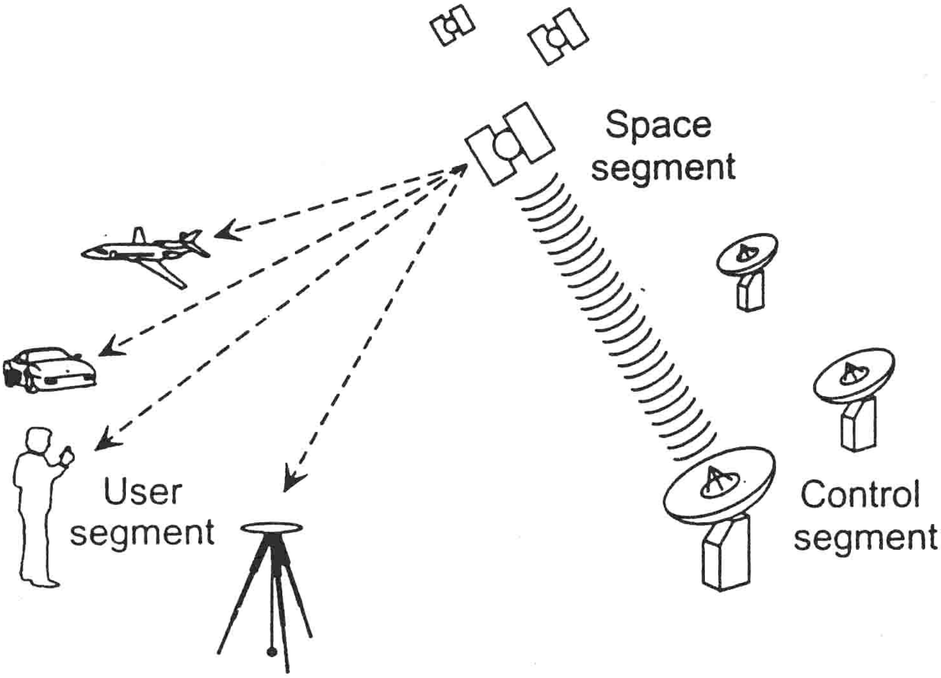

Figure 7.1 GPS system elements.

- Maintain accurate time by means of onboard atomic clocks, and
- Transmit information and signals to users on two L-band frequencies

Several constellations of GPS satellites have been deployed, and are planned. The first *experimental* satellite of the so-called 'Block I' constellation was launched in February 1978. The last of this 11 satellite series was launched in 1985. The *operational* constellation of GPS satellites, the 'Block II' and 'Block IIA' satellites, were launched from 1989 onwards. *Full Operational Capability* was declared on 17 July 1995 – the milestone reached when 24 'Block II/IIA' satellites were operating satisfactorily. There are 18 *replenishment* 'Block IIR' satellites, with the first launched in 1997. Currently 12 of these satellites are being redesigned as part of the 'GPS Modernization' program (see Section15.4.1). The 'Block IIF' *follow-on* satellite series is still in the design phase, and the satellites are planned for launch from 2006 onwards with similar enhancements as the latter 'Block IIR' satellites, as well as having the ability to transmit a third frequency. The status of the current GPS satellite constellation, and such details as the launch and official commissioning date, the orbital plane and position within the plane, the satellite ID number(s), etc. can be obtained from several electronic GPS information sources on the Internet, for example the US Coast Guard Navigation Center (NAVCEN 2001).

At an altitude of approximately 20,200 km, a constellation of 24 functioning GPS satellites, located in six orbital planes inclined at about 63° to the equator (Figure 7.2), is sufficient to ensure that there will be *at least four satellites visible*, at any unobstructed site on the earth, at any time of the day. As the GPS satellites are in nearly circular orbits:

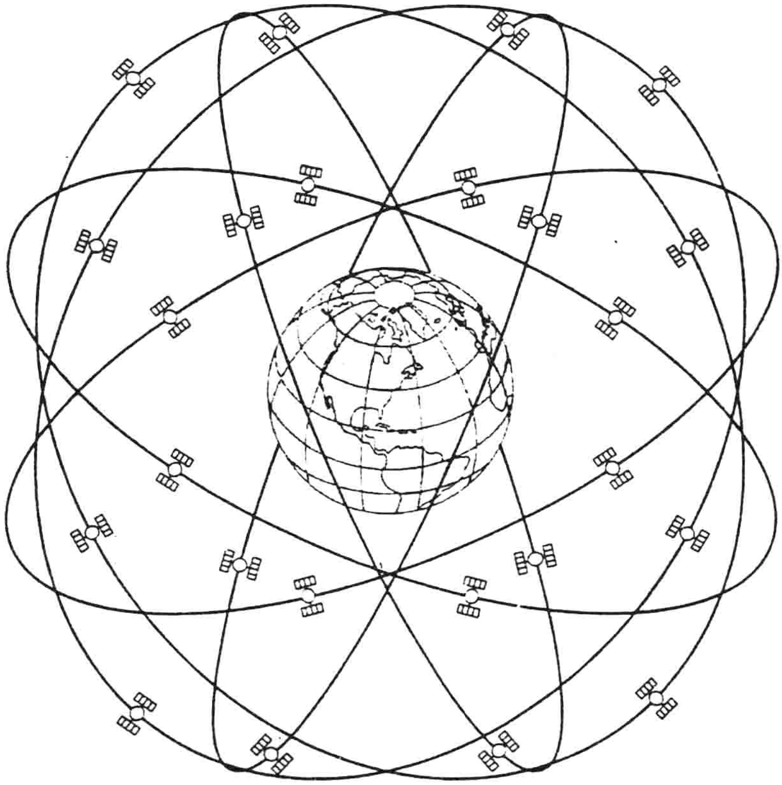

Figure 7.2 The GPS constellation 'birdcage' showing the 24 orbiting satellites.

- Their orbital period is approximately 11 h 58 min, so that each satellite makes two revolutions in one sidereal day (the period taken for the earth to complete one rotation about its axis with respect to the stars).
- At the end of a sidereal day the satellites are again over the same location on the earth.
- Reckoned in terms of a solar day (24 h in length), the satellites are in the same position in the sky about 4 min earlier each day.

Satellite visibility at any point on the earth, and for any time period, can be computed using 'mission planning' tools provided with standard GPS surveying software.

A GPS satellite may be above an observer's horizon for many hours, perhaps 6–7 h or more in the one pass. At various times of the day, and at various locations on the surface of the earth, the number of satellites and the length of time they are above an observer's horizon will vary. Although at certain times of the day there may be as many as 12 satellites visible simultaneously, there are nevertheless occasional periods of degraded satellite coverage (though naturally their frequency and duration will increase if satellites fail). 'Degraded satellite coverage' is typically defined in terms of the magnitude of the Dilution of Precision (DOP) factor, a measure of the quality of receiver-satellite geometry (see Section 9.3.3). The higher the DOP value, the poorer the satellite geometry.

Each GPS satellite transmits unique navigational signals centered on two L-band frequencies of the electromagnetic spectrum: L1 at 1575.42 MHz and L2 at 1227.60 MHz. (Two signals at different frequencies permit the ionospheric delay effect on the signal raypaths to be estimated – see Section 9.2.1.1, thus improving measurement accuracy.) At these two frequencies the signals are highly directional and can be reflected or blocked by solid objects. Clouds are easily penetrated, but the signals may be blocked by foliage (the extent of this is dependent on a number of factors, such as the type and density of the leaves and branches, and whether they are wet or dry, etc.). The satellite signal consists of the following components:

- Two L-band *carrier waves*
- *Ranging codes* modulated on the carrier waves
- Navigation message

The primary function of the ranging codes is to permit the *signal transit time* (from satellite to receiver) to be determined. The transit time when multiplied by the speed of light then gives a measure of the receiver-satellite 'range'. In reality the measurement process is more complex and the measurement is contaminated by a variety of biases and errors (Langley 1991b, 1993). The navigation message contains the satellite orbit (or ephemeris) information, satellite clock error parameters, and pertinent general system information necessary for real-time navigation to be performed. Although for positioning and timing the function of the GPS signal is quite straightforward, the stringent performance requirements of GPS are responsible for the complicated nature of the GPS signal structure. Table 7.1 summarizes the GPS system requirements and their corresponding implications on the signal characteristics (after Wells *et al.* 1986).

7.1.2. The control segment

The control segment consists of facilities necessary for satellite health monitoring, telemetry, tracking, command and control, and satellite orbit and clock error computations. There are currently five ground facility stations: Hawaii, Colorado Springs, Ascension Island, Diego Garcia and Kwajalein. All are operated by the US Department of Defense and perform the following functions:

- All five stations are *Monitor Stations*, equipped with GPS receivers to track the satellites. The resultant tracking data is sent to the Master Control Station (MCS).
- Colorado Springs is the *MCS* , where the tracking data are processed in order to compute the satellite ephemerides (or coordinates) and satellite clock error parameters. It is also the station that initiates all operations of the space segment, such as spacecraft maneuvering, signal encryption, satellite clock-keeping, etc.
- Three of the stations (Ascension Is., Diego Garcia, and Kwajalein) are *Upload Stations* through which data is telemetered to the satellites.

Each of the upload stations views all of the satellites at least once per day. All satellites are therefore in contact with an upload station several times a day, and new navigation messages as well as command telemetry can be transmitted to the GPS satellites on a regular basis. The computation of each satellite's ephemeris, and the determination of the each satellite's clock errors, are the most important tasks of

Table 7.1 GPS system requirements and the nature of GPS signal

System requirements	*Implication on GPS signals*
GPS has to be a multi-user system	• Signals can be simultaneously observed by unlimited numbers of users → Accomplished by one-way measurement to passive user equipment. • Signal has to have a relatively wide spatial coverage.
GPS has to provide real-time positioning and navigation capability for the users	• At a certain epoch, signals from several satellites have to be simultaneously observed by a single user → Each signal to have a unique code, so receiver can differentiate signals from different satellites. • Signal has to provide data for user to estimate range to the observed satellite in real-time → Signal has to enable time delay measurement by the user. • Signal has to provide the ephemeris data in real-time to the user → Ephemeris data is included in a broadcast message.
GPS has to serve both military and civilian users	• Signals have to provide two levels of accuracy for time delay measurements → Different codes for the military and civilian users. • Signal has to support the AS policy, in which the military code is encrypted to prevent unauthorized use.
GPS signal has to be resistant to jamming	• Requires a unique code structure. • Uses the 'spread spectrum' technique.
GPS can be used for precise positioning	• Provide range measurements at two frequencies, to compensate for ionospheric refraction effect. • Require carrier wave(s) with centimeter wavelength.

the control segment. The first is necessary because the GPS satellites function as 'orbiting control stations' and their coordinates must be known to a relatively high accuracy, while the latter permits a significant measurement bias to be reduced.

The product of the orbit computation process at the MCS is each satellite's *predicted ephemeris*, expressed in the reference system most appropriate for positioning: an *Earth-Centered-Earth-Fixed* (ECEF) reference system known as the World Geodetic System 1984 (WGS 84) (Chapter 3, Part 1). The accuracy with which the orbit is predicted is typically at the few meter level. The behavior of each GPS satellite clock is monitored against GPS Time, as maintained by an ensemble of atomic clocks at the MCS. The satellite clock *bias, drift* and *drift-rate* relative to GPS Time are explicitly determined at the same time as the estimation of the satellite ephemeris. The clock error behavior so determined is made available to all GPS users via clock error coefficients in a polynomial form broadcast in the navigation message (see Section 8.3.2). However, what is available to users is really a *prediction* of the clock behavior for some future time instant. Due to random deviations – even cesium and rubidium oscillators are not entirely predictable – the deterministic models of satellite clock error are only accurate to about 10 nanoseconds or so. This is not precise enough for range measurements that must satisfy the requirements of cm-level GPS positioning. Strategies have therefore to be implemented that will account for this *residual* range bias.

7.1.3. The user segment

This is the component of the GPS system with which users are most concerned – the space and control segments are largely transparent to the operations of the navigation function. Of interest is the range of GPS user applications, equipment, positioning strategies and data processing techniques that are now possible. The 'engine' of commercial GPS product development is, without doubt, the *user applications*. New applications are being continually identified, each with its unique requirements in terms of accuracy, reliability, operational constraints, user hardware, data processing algorithms, latency of the GPS results, and so on. As a result, GPS user equipment has undergone an extensive program of development that is continuing to this day. In this context, GPS *equipment* refers to the combination of hardware, software, and operational procedures or requirements. Chapter 9 discusses the various measurement models and data processing strategies, the hardware issues are introduced in Chapter 10, the various GPS techniques will be described in Chapter 11, while the field operations of relevance to precise GPS positioning will be dealt with in Chapters 12 and 13.

While military R&D has concentrated on achieving a high degree of miniaturization, modularization and reliability, the commercial equipment manufacturers have, in addition, sought to bring down costs and to develop features that enhance the capabilities of the positioning system. Civilian users have, from the earliest days of GPS availability, demanded increasing levels of performance, in particular higher accuracy, improved reliability and faster results. This is particularly true of the survey user seeking levels of accuracy several orders of magnitude higher than that required by the navigator. In some respects GPS user equipment development is being driven by the precise positioning applications – in much the same way that automotive technology often benefits from car racing. Another major influence on the development of GPS equipment has been the increasing variety of civilian applications. Although it is possible to categorize positioning applications according to many criteria, the most important from the perspective of geospatial applications are:

- Accuracy, which leads to a differentiation of the GPS user equipment and techniques into several sub-classes.
- Timeliness, whether the GPS results are required in real-time, or may be derived from post-mission data processing.
- Kinematics, distinguishing between static receiver positioning, and those applications in which the receiver is moving (or in the so-called 'kinematic' mode).

The different GPS positioning modes and data processing strategies are all essentially designed to account for biases (or systematic errors) in GPS measurements to different levels of accuracy (Section 7.3). In this regard there are two aspects of GPS that fundamentally influence the entire user segment: the user equipment, the data processing techniques, and the operational (field) procedures. They are:

1. The type of *measurement* that is used for the positioning solution (Sections 8.2 and 8.4). There is, on the one hand, the basic satellite-to-receiver 'range' measurements with a precision typically at the few meter level. However, for precise applications such as in surveying, carrier phase measurements must be used. These have precisions at the millimeter level, but require more complex data processing in order to realize cm-level positioning accuracy.
2. The *mode of positioning*, whether it is based on single-receiver techniques, or in terms of defining the position of one receiver relative to another that is located at a known position. Relative positioning is the standard mode of operation if accuracy better than a few meters is required, although the actual accuracy achieved depends on many factors.

7.1.3.1. Absolute positioning

In this mode of positioning the reference system must be rigorously defined and maintained, and total reliance is placed on the *integrity* of the coordinated points within the reference system. In general the coordinate origin of the coordinate system is the geocenter, and the axes of the system are defined in a conventional manner as in ECEF datums such as WGS 84 and ITRS (Section 7.2). Satellite single-point positioning is the process by which:

- *Given* the position vector of the satellite being tracked (in the global system), and
- *Given* a set of measurements from one or more ground tracking stations to the satellite (or satellites) being tracked;
- *Determine* the position vector of the ground station(s).

Some space geodesy technologies can determine the absolute position of a ground station to a very high accuracy, as for example in the satellite laser ranging (SLR) technique. However, the coordinates of a GPS receiver *in an absolute sense* are determined to a much lower accuracy than the precision of the measurements themselves, because it is not possible to fully account for the effects of measurement biases. Combining data from two GPS receivers is an effective way of eliminating or mitigating the effects of unmodeled measurement biases.

7.1.3.2. Relative positioning

Conceptually, relative position is the difference between the two position vectors (in the *global system*), expressed in a local reference system with origin at one of the ground stations. Most of the error in absolute position are common to both sets of coordinates (due to the similar biases on all GPS measurements), and hence largely cancel from the baseline components. In this case the positioning accuracy approaches that of the basic measurement precision itself.

There are different ways in which such differential positioning can be implemented using GPS. Data processing techniques such as those implemented for GPS surveying are essentially concerned with the determination of the *baseline components* between simultaneously observing receivers (Figure 7.3).

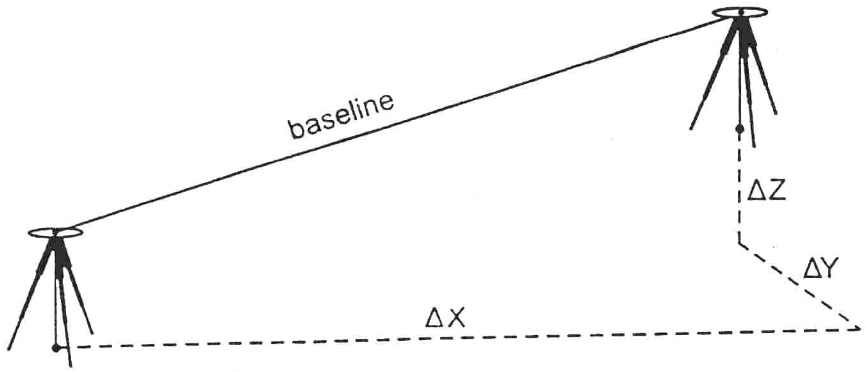

Figure 7.3 The baseline linking two simultaneously observing GPS receivers.

7.2. The issue of GPS datums

Chapter 3, Part 1, introduced the concept of datums and geodetic systems. In this section the modern geodetic reference systems are discussed from the viewpoint of GPS positioning.

7.2.1. WGS 84 system

The WGS 84 is defined and maintained by the US National Imagery and Mapping Agency (NIMA) as a *global geodetic datum* (NIMA 1997). It is the datum to which all GPS positioning information is referred by virtue of being the reference system of the broadcast GPS satellite ephemerides (Langley 1991a). The *realization* of the WGS 84 satellite datum is the catalogue of coordinates of over 1,500 geodetic stations (most of them active or past tracking stations) around the world. They fulfil the same function as national control benchmarks, that is, they provide the means by which a position can be related to a datum.

The relationship between WGS 84 (as well as other global datums) and local geodetic datums have been determined empirically (NIMA 1997), and transformation models of varying quality have been developed. Reference systems are periodically redefined, for various reasons, and the result is generally a small refinement in the datum definition, and a change in the numerical values of the coordinates of benchmarks. However, with dramatically improving tracking accuracy another phenomenon impacts on datum definition and its maintenance: *the motion of the tectonic plates across the earth's surface* (or 'continental drift'). This motion is measured in centimeters per year, with the fastest rates being over 10 cm/year. Nowadays this motion can be monitored and measured to sub-centimeter accuracy, on a global annual-average basis. In 1994 the GPS reference system underwent a subtle change to WGS 84(G730) to bring it into alignment with the same system as used by the International GPS Service to generate its precise GPS ephemerides. Another small change was made in 1996.

7.2.2. The international terrestrial reference frame

The WGS 84 system is the most widely used global reference system because it is the system in which the GPS satellite coordinates are expressed in the navigation message. Other satellite reference systems have been defined but these have mostly been for scientific purposes. However, since the mid 1980s geodesists have been using GPS to measure crustal motion, and to define more precise satellite datums. The latter were essentially by-products of the sophisticated data processing, which included the computation of the GPS satellite orbits. These surveys required coordinated tracking by GPS receivers spread over a wide region during the period of GPS survey 'campaigns'. Little interest was shown in these alternative datums until the network of tracking stations evolved into a *global one* that was maintained on a *permanent basis*, and the scientific community initiated a *project to define and maintain a datum at the highest level of accuracy*.

In 1991, the International Association of Geodesy decided to establish the International GPS Service for Geodynamics (IGS – nowadays the acronym 'IGS' stands for the 'International GPS Service') to promote and support activities such as the maintenance of a permanent network of GPS tracking stations, and the continuous computation of the satellite ephemerides and ground station coordinates. Both of these were preconditions to the definition and maintenance of a new satellite datum independently of the tracking network used to maintain the WGS 84 datum (and to provide the data for the computation of the GPS broadcast ephemerides). Routine activities commenced at the beginning of 1994 and the network now consists of about 50 core tracking stations located around the world, supplemented by more than 100 other stations (IGS 2001). The precise orbits of the GPS satellites (and other products) are available from the IGS via the Internet.

The definition of the reference system in which the coordinates of the IGS tracking stations are expressed and periodically re-determined is the responsibility of the International Earth Rotation Service (IERS). The reference system is known as the *International Terrestrial Reference System* (ITRS), and its definition and maintenance is dependent on a suitable combination of satellite laser ranging (SLR), very long baseline interferometry (VLBI) and GPS coordinate results (although increasingly it is the GPS system that is providing most of these data). Every other year a new combination of precise tracking results is performed, and the resulting new coordinates of SLR, VLBI and GPS tracking stations constitutes a new *International Terrestrial Reference Frame* (ITRF) or 'ITRF datum' which is referred to as 'ITRF yy', where 'yy' is the comput-ation year identifier. A further characteristic that sets the ITRS series of datums apart from WGS 84 is that the definition not only consists of the station coordinates, but also their *velocities* (due to continental and regional tectonic motion). Hence, it is possible to determine station coordinates within the datum, say ITRF 97, at some *epoch* such as the year 2000, by applying the velocity information and predicting the coordinates of the station at any time into the future (or the past). For example, the WGS 84(G730) reference system is identical to that of ITRF 91 at epoch 1994.0.

Such ITRS datums, initially dedicated to geodynamical applications requiring the highest possible precision, have been used increasingly as the fundamental basis for the redefinition of many nations geodetic datums. For example, the new Australian datum

– the Geocentric Datum of Australia 1994 – is defined as ITRF 92 at epoch 1994.0 (AUSLIG 2001). Of course countries are free to chose any of the ITRS datums (it is usually the latest), and define any epoch for their national datum (the year of GPS survey, or some reference date such as the year 2000). Only if both the ITRS datum (the designated ITRF yy) and the epoch are the same, can it be claimed that two countries have the same geodetic datum.

7.3. The performance of GPS

As far as users are concerned, there are a number of '*measures of performance*'. For example, how many observations are required to assure a certain level of accuracy is one measure that is important for survey-type applications. The less time required to collect observations, the more *productive* the GPS is, because productivity is closely related to the 'number of surveyed points per day'. Another measure of performance might be the maximum distance between two GPS receivers that would still assure a certain level of accuracy. However, the most common measure of performance is the positioning *accuracy*.

7.3.1. Factors influencing GPS accuracy

Biases and *errors* affect all GPS measurements. GPS biases may have the following characteristics:

1 Affect all measurements made by a receiver by an equal (or similar) amount.
2 Affect all measurements made to a particular satellite by an equal (or similar) amount.
3 Unique to a particular receiver-satellite observation.

7.3.1.1. Biases and errors

Their combined magnitude will affect the accuracy of the positioning results. Errors may be considered synonymous to internal instrument noise or *random errors*. Biases, on the other hand, may be defined as being those measurement errors that cause *true ranges* to be different from *measured ranges* by a 'systematic amount', such as, for example, all distances being measured either too short, or too long.

In the case of GPS, a very significant bias was *Selective Availability* (SA), a policy of the US government imposed on 25 March 1990, and finally revoked on the 1 May 2000. SA was a bias that caused all distances from a particular satellite, at an instant in time, to be in error by up to several tens of meters. The magnitude of the SA-induced bias varied from satellite-to-satellite, and over time, in an unpredictable manner. The policy *Anti-Spoofing* (AS), on the other hand, although not a signal bias, does affect positioning accuracy as it prevents civilian users access to the second GPS signal frequency. Measurements on two frequencies simultaneously is the best means by which the ionospheric refraction delay can be accounted for.

Biases must somehow be accounted for in the measurement model used for data processing if high accuracy is sought. There are several sources of bias with varying characteristics of magnitude, periodicity, satellite or receiver dependency, etc. Biases may have physical bases, such as the atmosphere effects on signal propagation, but may also enter at the data processing stage through imperfect knowledge of constants, for example any 'fixed' parameters such as the satellite orbit, station coordinates, etc. *Residual biases* may therefore arise from incorrect or incomplete observation modeling, and hence it is useful to assemble under the heading of 'errors' all random measurement process effects, as well as any unmodeled biases that remain after 'data reduction'.

7.3.1.2. Absolute and relative positioning

There are two GPS positioning modes which are fundamental to considerations of: (a) *bias propagation* into (and hence accuracy of) GPS results, and (b) the *datum* to which the GPS results refer. The first is *absolute or point positioning*, with respect to a well-defined coordinate system such as WGS 84 or the ITRS, and is often referred to as *Single-Point Positioning*. As the satellite coordinates are essential for the computation of user position, any error in these values (as well as the presence of other biases) will directly affect the quality of the position determination. The satellite-receiver geometry will also influence the error propagation into the GPS positioning results.

Higher accuracy is possible if the relative position of two GPS receivers, simultaneously tracking the same satellites, is computed. Because many errors will affect the absolute position of two or more GPS users to almost the same extent, these errors largely cancel when *differential or relative positioning* is carried out. This was particularly effective in overcoming the effect of SA-induced biases. There are different implementations of differential positioning procedures but all share the characteristic that the position of the GPS receiver of interest is derived *relative* to another fixed, or *reference*, receiver whose absolute coordinates are assumed to be known. One of these implementations, based on differencing the carrier phase data from the two receivers, is the standard mode for precise GPS techniques (Section 8.6.2).

7.3.1.3. Other factors influencing accuracy

Finally, GPS accuracy is also dependent on a host of other *operational, algorithmic and other factors*:

- Whether the user is moving or stationary. Clearly repeat observations at a static benchmark permit an improvement in precision due to the effect of averaging over time. A moving GPS receiver does not offer this possibility and the accuracy is dependent on single-epoch processing.
- Whether the results are required in real-time, or if post-processing of the data is possible. The luxury of post-processing the data permits more sophisticated modeling of the GPS data in order to improve the accuracy and reliability of the results.
- The level of measurement noise has a considerable influence on the precision attainable with GPS. Low measurement noise would be expected to result in comparatively high accuracy. Hence carrier phase measurements are the basis for high accuracy techniques (Section 8.4), while pseudorange measurements are used for comparatively low accuracy applications (Section 8.2).

- The degree of redundancy in the solution as provided by extra measurements, which may be a function of the number of tracked satellites as well as the number of observables (e.g. carrier phase and pseudorange data on L1 and L2).
- The algorithm type may also impact on GPS accuracy (although this is largely influenced by the observable being processed and the mode of positioning). In the case of carrier phase-based positioning, to ensure cm-level accuracy it is crucial that a so-called 'ambiguity-fixed' solution be obtained (Section 9.4.3).
- 'Data enhancements' and 'solution aiding' techniques may be employed. For example, the use of carrier phase-smoothed pseudorange data, external data such as from inertial navigation systems (and other such devices), additional constraints, etc.

7.3.2. Accuracy versus positioning mode

Figure 7.4 illustrates the different positioning accuracy associated with the different GPS positioning modes (accuracy is quoted as two-sigma values, i.e. 95 per cent confidence level). The following comments may be made with respect to this diagram:

1 The top half refers to Single-Point Positioning (SPP), the lower half to the relative positioning mode.
2 The basic SPP services provided by the US Department of Defense are the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS), both intended

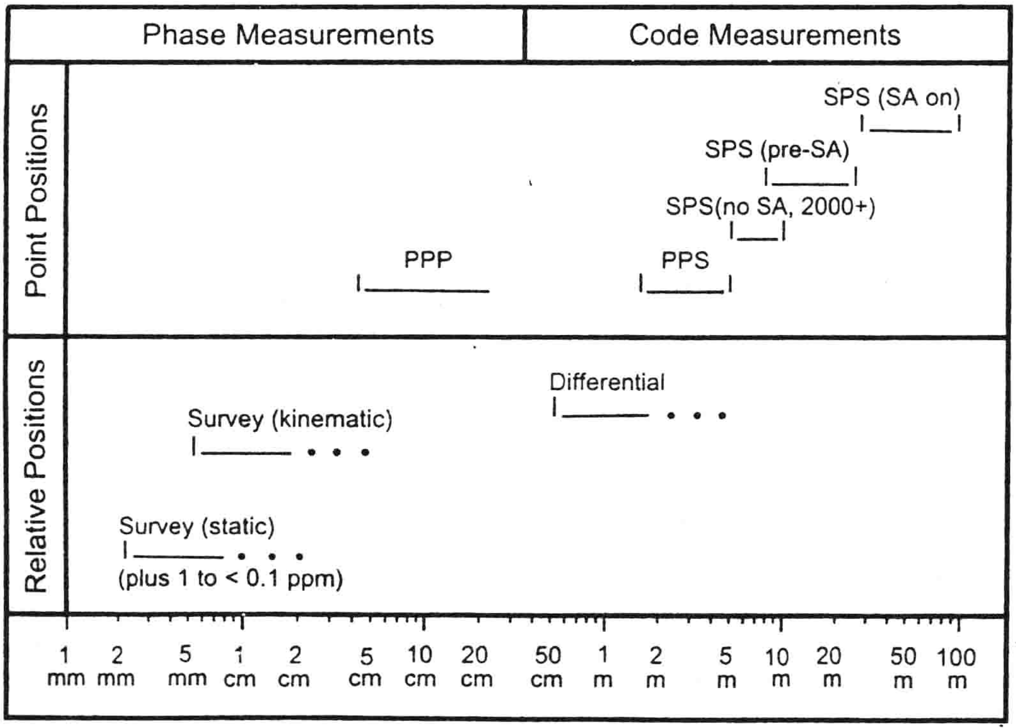

Figure 7.4 GPS accuracy and positioning modes.

for single-epoch positioning.

3. There is a wide range of horizontal SPS and PPS accuracy possible due to a variety of factors:
   a. 100 m level accuracy SPS positioning with SA on, *as a result of an artificial degradation of the system.*
   b. 5–15 m level accuracy of SPS positioning without SA, representing the current 'natural' accuracy ceiling when using basic navigation-type GPS receivers, because of the difficulty in accounting for the ionospheric bias in the single-frequency C/A-code measurements.
   c. 10–50 per cent improvement is possible using dual-frequency GPS receivers.
   d. 2–10 m level accuracy PPS positioning, using dual-frequency P-code pseudo-range measurements.
   e. Dual-frequency GPS, coupled with the high accuracy satellite clock and ephemeris data provided by the IGS, can deliver a 50 per cent improvement in basic SPS accuracy.
4. Surprisingly, the averaging of SPS results for up to 60 min at a single benchmark does not significantly improve positioning accuracy, with recent studies indicating an improvement of the order of 10–20 per cent compared to single-epoch solutions.
5. The carrier phase-based procedures are typically only applied in the relative positioning mode for most engineering, surveying and geodetic applications, and *relative* position accuracy is usually expressed in terms of *parts per million* ('ppm' – e.g. 1 cm error in 10 km).
6. Carrier phase-based positioning may be in the single-epoch mode (as is necessary for kinematic positioning), or takes advantage of the receiver being static in order to collect data over an *observation session.*
7. *Precise Point Positioning* is possible using carrier phase data, with accuracies better than a decimeter possible if the observation session is several hours in length (Section 14.2.3).
8. The accuracy of carrier phase-based positioning techniques is a function of baseline length, number of observations, length of observation session, whether ambiguities have been fixed to their integer values or not, and others.
9. In all cases, the vertical accuracy is about 2–3 times worse than the horizontal positioning accuracy.

The 'resolution of the carrier phase ambiguities' is central to precise carrier phase-based positioning in many surveying and engineering applications and requires the determination of the exact number of integer wavelengths in the carrier measurement of satellite-to-receiver distance (Section 9.4.2).

It should be emphasized that GPS was originally designed to provide accuracies of the order of a *dekameter* (ten meters) or so in the SPP mode, and is optimized for real-time operations. All other developments to improve this basic accuracy capability must be viewed in this context. As a general axiom of GPS positioning, the higher the accuracy sought, the more effort (in time, instrumentation and processing sophistication) that is required.

7.4. High precision GPS positioning

GPS is having a profound impact on society. It is estimated that the worldwide market for GPS receiver equipment in 2000 was about US$10 billion, but the annual market for services may be several times this value! Market surveys suggest that the greatest growth is expected to be consumer markets such as in-vehicle applications, integration of GPS and cellular phones, and portable GPS for outdoor recreation and similar activities. These are expected to ultimately account for more than 60 per cent of the GPS market. The penetration of GPS into many applications (and in particular into consumer devices) helps make the processes and products of geospatial information technology more and more a part of the mainstream 'information society'. However, in the following chapters the focus will be on the surveying and mapping disciplines, and how GPS is now an indispensable tool for geospatial professionals.

7.4.1. GPS in support of geospatial applications

In this manual the authors have adopted a very broad definition of 'GPS surveying', encompassing all applications where coordinate information is sought in support of mapping or geospatial applications. In general such applications:

- Are of *comparatively high accuracy*. This is, of course, a subjective judgement, but in general 'high accuracy' implies a level of coordinate precision much higher than originally intended of GPS. As GPS is a navigation system designed to deliver dekameter-level SPP accuracy, the accuracy threshold for *surveying* may be arbitrarily set at the sub-meter level, while *mapping* accuracy's may be satisfied by Differential GPS (DGPS) techniques that can deliver accuracy's at the few meter level. *In this manual 'GPS surveying' will be considered synonymous with carrier phase-based positioning.*
- Require the use of *unique observation procedures, measurement technologies and data analysis*. In fact, the development of distinctive field procedures, specialized instrumentation and sophisticated software is the hallmark of 'GPS surveying'.
- Do *not require positioning information 'urgently'*. 'Navigation', on the other hand, is concerned with the safe passage of vehicles, ships and aircraft, and hence demands location information in *real-time*.
- In general permits *post-processing of data* to obtain the highest accuracy possible.
- Has as its raison d'entre, the *production of a map*, or the establishment of a *network of coordinated points* which support the traditional tasks of the surveying discipline, as well as new applications such as GIS.

In the case of *land surveying applications*, the characteristics of GPS satellite surveying are:

1. The points being coordinated are generally *stationary*.
2. Depending on the accuracy sought, GPS *data are collected over some 'observation session'*, ranging in length from a few seconds to several hours, or more.
3. Restricted to the relative positioning mode of operation.
4. In general (depending on the accuracy sought) the measurements used for the data reduction are those made on the satellites *L-band carrier waves*.

5. Generally associated with the *traditional surveying and mapping functions*, but accomplished using GPS techniques in less time, to a higher accuracy (for little extra effort) and with greater efficiency.

A convenient approach is to adopt a geospatial applications classification on the basis of accuracy requirements. Four classes can be identified on this basis:

Scientific Surveys (category A):	better than 1 ppm
Geodetic Surveys (category B):	1–10 ppm
General Surveying (category C):	lower than 10 ppm
Mapping/Geolocation (category D):	better than 2 m

Category A primarily consist of those surveys undertaken in support of precise engineering, deformation analysis, and geodynamic applications. Category B includes geodetic surveys undertaken for the establishment, densification and maintenance of control networks. Category C primarily encompasses lower accuracy surveys, primarily to support engineering and cadastral applications, geophysical prospecting, etc. Category D includes all other general purpose 'geolocation' surveys intended to coordinate objects or features for map production and GIS data capture (Chapter 25, Part 4). Users in the latter two categories form the majority of the GPS user community. Category A and B users may provide the 'technology-pull' impetus for the development of new instrumentation and processing strategies, which may ultimately be adopted by the category C and D users. Note, this classification scheme is entirely *arbitrary*, and does not relate to any specification of 'order' or 'class' of survey as may be defined by national or state survey agencies.

7.4.2. Using GPS in the field

With respect to category D users (using the pseudorange-based techniques), the planning issues, as well as the field and office procedures, are not as stringent as for the GPS surveying users. Hence most of the attention will be focused on carrier phase-based techniques. Some comments to the *operational aspects* of GPS surveying (categories A, B, C above):

1. Survey planning considerations are derived from:
    - a The nature and aim of the survey project – *as for conventional surveys.*
    - b The unique characteristics of GPS, and in particular no requirement for receiver intervisibility – *a simplification in survey design.*
    - c The number of points to be surveyed, the resources at the surveyor's disposal, and the strategy to be used for propagating the survey – *a logistical challenge.*
    - d Prudent survey practice, requiring redundant and check measurements to be incorporated into the network design.
2. Field operations are characterized by requirements for:
    - a Clear skyview.
    - b Setup of antennas over ground marks.
    - c Simultaneous operation of two or more GPS receivers.