

Antennas for Global Navigation Satellite Systems

Xiaodong Chen

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 WILEY

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Preface

The global navigation satellite system (GNSS) is becoming yet another pillar technology in today's society along with the Internet and mobile communications. GNSS offers a range of services, such as navigation, positioning, public safety and surveillance, geographic surveys, time standards, mapping, and weather and atmospheric information. The usage of GNSS applications has become nearly ubiquitous from the ever-growing demand of navigation facilities made available in portable personal navigation devices (PNDs). Sales of mobile devices including smart phones with integrated GNSS are expected to grow from 109 million units in 2006 to 444 million units in 2012, and this sector of industry is second only to the mobile phone industry. The navigation industry is predicted to earn a gross total of \$130 billion in 2014. The current developments and expected future growth of GNSS usage demand the availability of more sophisticated terminal antennas than those previously deployed.

The antenna is one of most important elements on a GNSS device. GNSS antennas are becoming more complex every day due to the integration of different GNSS services on one platform, miniaturisation of these devices and performance degradations caused by the user and the local environment. These factors should be thoroughly considered and proper solutions sought in order to develop efficient navigation devices. The authors have been active in this research area over the last decade and are aware that a large amount of information on GNSS antenna research is scattered in the literature. There is thus a need for a coherent text to address this topic, and this book intends to fill this knowledge gap in GNSS antenna technology. The book focuses on both the theory and practical designs of GNSS antennas. Various aspects of GNSS antennas, including the fundamentals of GNSS and circularly polarised antennas, design approaches for the GNSS terminal and satellite antennas, performance enhancement techniques used for such antennas, and the effects of a user's presence and the surrounding environment on these antennas, are discussed

in the book. Many challenging issues of GNSS antenna design are addressed giving solutions from technology and application points of view.

The book is divided into eight chapters.

Chapter 1 introduces the concept of GNSS by charting its history starting from DECCA land-based navigation in the Second World War to the latest versions being implemented by the USA (GPS), Europe (GLONASS and Galileo) and China (Compass). The fundamental principles of time delay navigation are addressed and the operation of the US NAVSTAR GPS is described. The enhanced applications of the GPS are addressed including its use as a time reference and as an accurate survey tool in its differential form.

Chapter 2 describes radio wave propagation between the GNSS satellite and the ground receiver and the rationale for selecting circularly polarised (CP) waves. It also introduces the relevant propagation issues, such as multipath interference, RF interference, atmospheric effects, etc. The fundamental issues in GNSS antenna design are highlighted by presenting the basic approaches for designing a CP antenna.

Chapter 3 covers the requirements for spacecraft GNSS antennas illustrating the descriptions of typical deployed systems for both NAVSTAR GPS and Galileo. The various special performance requirements and tests imposed on spacecraft antennas, such as passive intermodulation (PIM) testing and multipactor effects, are also discussed.

Chapter 4 deals with the specifications, technical challenges, design methodology and practical designs of portable terminal GNSS antennas. It introduces various intrinsic types of terminal antennas deployed in current GNSSs, including microstrip, spiral, helical and ceramic antennas.

Chapter 5 is dedicated to multimode antennas for an integrated GNSS receiver. The chapter presents three kinds of multimode GNSS antennas, namely dual-band, triple-band and wideband antennas. Practical and novel antenna designs, such as multi-layer microstrip antennas and couple feed slot antennas, are discussed. It also covers high-precision terminal antennas for the differential GPS system, including phase centre determination and stability.

Chapter 6 discusses the effects of the multipath environment on the performance of GNSS antennas in mobile terminals. It highlights the importance of statistical models defining the environmental factors in the evaluation of GNSS antenna performance and proposes such a model. It then presents a detailed analysis of the performance of various types of mobile terminal GNSS antennas in real working scenarios using the proposed model. Finally, it describes the performance enhancement of the terminal antennas in difficult environments by employing the techniques of beamforming, antenna diversity, A-GPS and ESTI standardised reradiating.

Chapter 7 deals with the effects of the human user's presence on the GNSS antennas, presenting details of the dependency of antenna performance on varying antenna–body separations, different on-body antenna placements and varying body postures. It also considers the effects of homogeneous and inhomogeneous human body models in the vicinity of the GNSS antennas. Finally, it discusses the performance of these antennas in the whole multipath environment operating near the human body, using a statistical modelling approach and considering various on-body scenarios.

Chapter 8 describes the limitations of both antenna size and shape that are imposed when GNSS functions are to be added to small devices such as mobile handsets and personal trackers. It is shown how the radiation patterns and polarisation properties of the antenna can be radically changed by factors such as the positioning of the antenna on the platform. The presence of a highly sensitive receiver system imposes severe constraints on the permitted levels of noise that may be generated by other devices on the platform without impairing the sensitivity of the GPS receiver. The chapter gives the steps which must be taken to reduce these to an acceptable level. The case studies cover a range of mobile terminal antennas, such as small backfire helices, CP patches and various microstrip antennas.

This is the first dedicated book to give such a broad and in-depth treatment of GNSS antennas. The organisation of the book makes it a valuable practical guide for antenna designers who need to apply their skills to GNSS applications, as well as an introductory text for researchers and students who are less familiar with the topic.

1

Fundamentals of GNSS

1.1 History of GNSS

GNSS is a natural development of localised ground-based systems such as the DECCA Navigator and LORAN, early versions of which were used in the Second World War. The first satellite systems were developed by the US military in trial projects such as *Transit*, *Timation* and then *NAVSTAR*, these offering the basic technology that is used today. The first NAVSTAR was launched in 1989; the 24th satellite was launched in 1994 with full operational capability being declared in April 1995. NAVSTAR offered both a civilian and (improved accuracy) military service and this continues to this day. The system has been continually developed, with more satellites offering more frequencies and improved accuracy (see Section 1.3).

The Soviet Union began a similar development in 1976, with GLONASS (GLOBAL NAVIGATION Satellite System) achieving a fully operational constellation of 24 satellites by 1995 [1]. GLONASS orbits the Earth, in three orbital planes, at an altitude of 19 100 km, compared with 20 183 km for NAVSTAR. Following completion, GLONASS fell into disrepair with the collapse of the Soviet economy, but was revived in 2003, with Russia committed to restoring the system. In 2010 it achieved full coverage of the Russian territory with a 20-satellite constellation, aiming for global coverage in 2012.

The European Union and European Space Agency *Galileo* system consists of 26 satellites positioned in three circular medium Earth orbit (MEO) planes at 23 222 km altitude. This is a global system using dual frequencies, which aims to offer resolution down to 1 m and be fully operational by 2014. Currently (end 2010) budgetary issues mean that by 2014 only 18 satellites will be operational (60% capacity).

Compass is a project by China to develop an independent regional and global navigation system, by means of a constellation of 5 geostationary orbit (GEO) satellites and 30 MEO satellites at an altitude of 21 150 km. It is planned to offer services to customers in the Asia-Pacific region by 2012 and a global system by 2020.

QZSS (Quasi-Zenith Satellite System) is a Japanese regional proposal aimed at providing at least one satellite that can be observed at near zenith over Japan at any given time. The system uses three satellites in elliptical and inclined geostationary orbits (altitude 42 164 km), 120° apart and passing over the same ground track. It aims to work in combination with GPS and Galileo to improve services in city centres (so called *urban canyons*) as well as mountainous areas. Another aim is for a 1.6 m position accuracy for 95% availability, with full operational status expected by 2013.

It is likely that many of these systems will offer the user interoperability leading to improved position accuracy in the future. It has already been shown that a potential improvement in performance by combining the GPS and Galileo navigation systems comes from a better satellite constellation compared with each system alone [2]. This combined satellite constellation results in a lower dilution of precision value (see Section 1.3), which leads to a better position estimate. A summary of the various systems undertaken during the first quarter of 2011 is shown in Table 1.1.

1.2 Basic Principles of GNSS

1.2.1 Time-Based Radio Navigation

The principle of GNSSs is the accurate measurement of distance from the receiver of each of a number (minimum of four) of satellites that transmit accurately timed signals as well as other coded data giving the satellites' position. The distance between the user and the satellite is calculated by knowing the time of transmission of the signal from the satellite and the time of reception at the receiver, and the fact that the signal propagates at the speed of light. From this a 3D ranging system based on knowledge of the precise position of the satellites in space can be developed. To understand the principles, the simple offshore maritime 2D system shown in Figure 1.1 can be considered. Imagine that transmitter 1 is able to transmit continually a message that says 'on the next pulse the time from transmitter 1 is ...', this time being sourced from a highly accurate (atomic) clock. At the mobile receiver (a ship in this example) this signal is received with a time delay ΔT_1 ; the distance D_1 from the transmitter can then be determined based on the signal propagating at the

Table 1.1 Summary of GNSS systems undertaken during Q1 2011

GNSS	GPS/NAVSTAR	GLONASS	Galileo	Compass	QZSS
Operational	Now	Now	2014 (for 14 satellites)	2012 regional 2020 global	2013
Constellation	24 MEO	24 MEO	27 MEO	5 GEO + 30 MEO	3 highly inclined elliptical orbits
Orbital altitude (km)	20 183	19 100	23 222	21 150 + GEO	42 164
Coverage	Global	Regional (Russia) then global	Global	Regional (Asia-Pacific) then global	Regional (East Asia and Oceania), augmentation with GPS
Position accuracy (civilian)	7.1 m 95%	7.5 m 95%	4 m (dual freq.)	10 m	1.6 m 95%
User Frequency bands (MHz)	L1 = 1575.420 L2 = 1227.6 L5 = 1176.45	G1 = 1602.0 G2 = 1246.0 G3 = 1204.704	E1 = 1575.42 E6 = 1278.75 E5 = 1191.795 E5a = 1176.45 E5b = 1207.14	B1 = 1561.098 B2 = 1207.14 B3 = 1268.52	L1 L2 L5 LEX = 1278.75 (for Differential GPS)
User coding and modulation	CDMA BPSK	FDMA BPSK + CDMA on GLONASS-K1	CDMA BOC and BPSK	QPSK and BOC	CDMA BPSK, BOC
Services and bandwidth	SPS on L1 with 2.046 MHz BW PPS on L1 & L2 with 20.46 MHz BW L2C (by 2016) L5 (by 2018) 20.46 MHz BW		Open on E1 with 24.552 MHz BW Open on E5a + E5b both 20.46 MHz BW	Open on B1 with 4.092 MHz BW Open on B2 with 24 MHz BW	L1 24 MHz BW, L2 24 MHz BW, L5 24.9 MHz BW

CDMA: Code Division Multiple Access; FDMA: Frequency Division Multiple Access; BPSK: Binary Phase Shift Keying; QPSK: Quadrature Phase Shift Keying; BOC: Binary Offset Carrier; SPS: Standard Positioning Service; PPS: Precision Positioning Service;

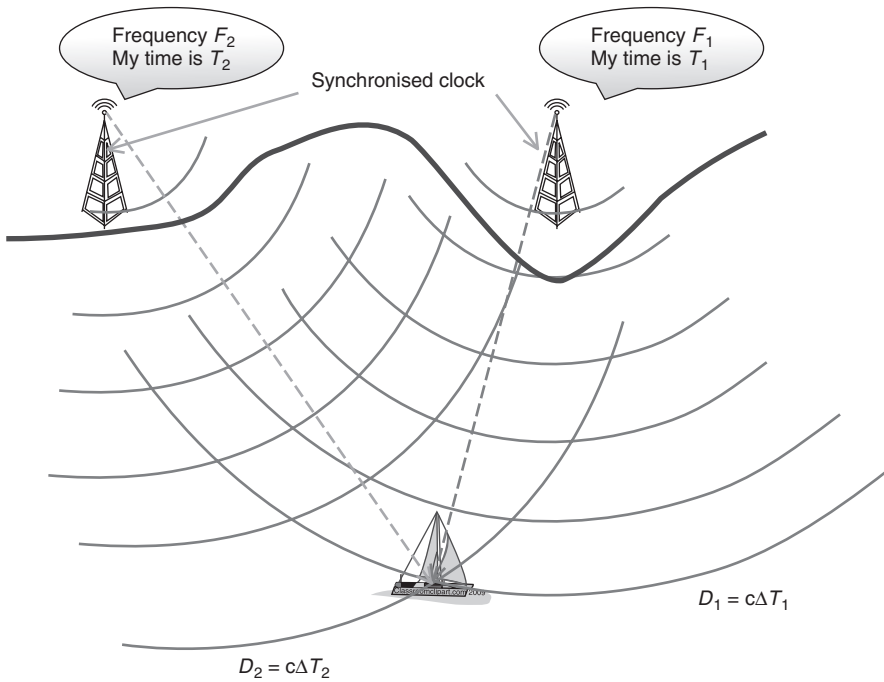


Figure 1.1 Simple 2D localised ship-to-shore location system.

speed of light c , from $D_1 = c\Delta T_1$. The same process can be repeated for transmitter 2, yielding a distance D_2 . If the mobile user then has a chart showing the accurate location of the shore-based transmitter 1 and transmitter 2, the user can construct the arcs of constant distance D_1 and D_2 and hence find his or her location. For this system to be accurate all three clocks (at the two transmitters and on board the ship) must be synchronised. In practice it may not be that difficult to synchronise the two land-based transmitters but the level of synchronisation of the ship-based clock will fundamentally determine the level of position accuracy achievable. If the ship's clock is in error by $\pm 1\mu\text{s}$ then the position error will be $\pm 300\text{m}$, since light travels 300 m in a microsecond. This is the fundamental problem with this simplistic system which can be effectively thought of as a problem of *two equations with two unknowns* (the unknowns being the ship's u_x, u_y location). However, in reality we have a third unknown, which is the ship's clock offset with respect to the synchronised land-based transmitters' clock. This can be overcome by adding a third transmitter to the system, providing the ability to add a third equation determining the u_x, u_y location of the ship and so giving a three-equation,

three-unknown solvable system of equations. We will explore this in detail later when we consider the full 3D location problem that is GNSS. As a local coastal navigation system this is practical since all ships will be south of the transmitters shown in Figure 1.1.

At this point it is worth noting the advantages of this system, the key one being that the ship requires no active participation in the system; it is only required to listen to the transmissions to determine its position. Thus, there is no limit on the number of system users and, because they are receive only, they will be relatively low cost for the ship owner.

1.2.2 A 3D Time-Based Navigation System

We can extend this basic concept of time-delay-based navigation to determine a user's position in three dimensions by moving our transmitters into space and forming a constellation surrounding the Earth's surface, Figure 1.2. In order

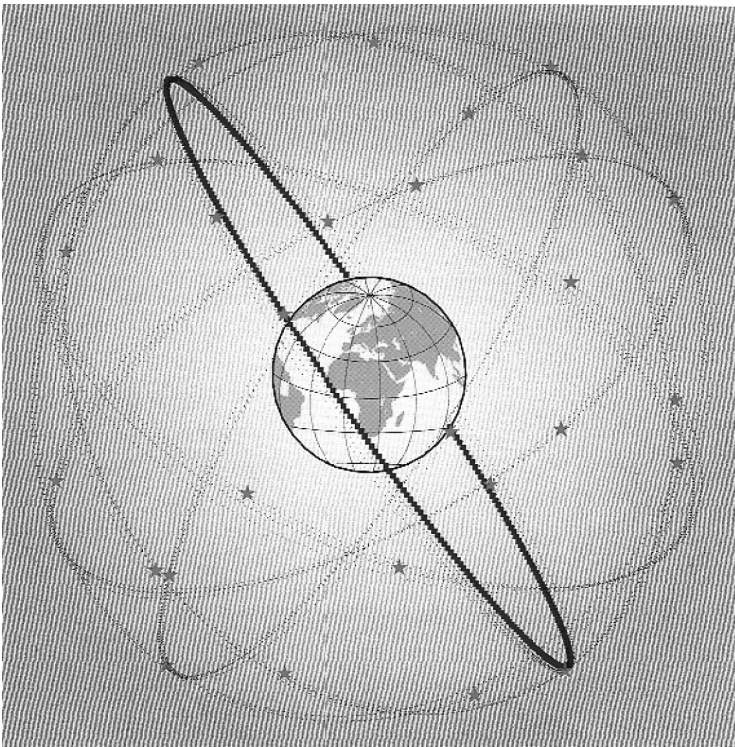


Figure 1.2 Satellite constellation [5].

for such a system to operate the user would be required to see (i.e. have a direct line of sight to) at least four satellites at any one time. This time *four* transmitters are required as there are now four unknowns in the four equations that determine the distance from a satellite to a user, these being the user's coordinates (u_x, u_y, u_z) and the user's clock offset ΔT with respect to *GPS time*. The concept of GPS time is that all the clocks on board all the satellites are reading exactly the same time. In practice they use one (or more) atomic clocks, but by employing a series of ground-based monitoring stations each satellite clock can be checked and so any offset from GPS time can be transmitted to the satellite and passed on to the user requiring a position fix.

The (x, y, z) location of each satellite used in a position fix calculation must be accurately known, and although Kepler's laws of motion do a very good job in predicting the satellite's location, use of the above-mentioned monitoring stations can offer minor position corrections. These monitoring stations (whose accurate position is known) can be used to determine accurately the satellite's orbital location and thus send to each satellite its orbital position corrections, which are then reported to the users via the GPS transmitted signal to all users. So each satellite would effectively transmit 'on the next pulse the time is ..., my clock offset from GPS time is ..., my orbital position correction is ...'.

A sketch of a four-satellite position location is shown in Figure 1.3 and the corresponding equation for the raw distance R_1 between the user terminal and satellite 1 is

$$R_1 = c(\Delta t_1 + \Delta T - \tau_1) \quad (1.1)$$

where Δt_1 is the true propagation delay from satellite 1 to the user terminal, τ_1 is the GPS time correction for satellite 1, and ΔT is the unknown user terminal clock offset from GPS time. Let the corrected range to remove the satellite 1 clock error be R'_1 . Then

$$R'_1 = c(\Delta t_1 + \Delta T) \quad (1.2)$$

The true distance between satellite 1 and the user terminal is then

$$C \Delta t_1 = R'_1 - c \Delta t = R'_1 - C_B \quad (1.3)$$

where C_B is fixed for a given user terminal at a given measurement time. In Cartesian coordinates the equation for the distance between the true satellite 1 position (x_1, y_1, z_1) , which has been corrected at the user terminal

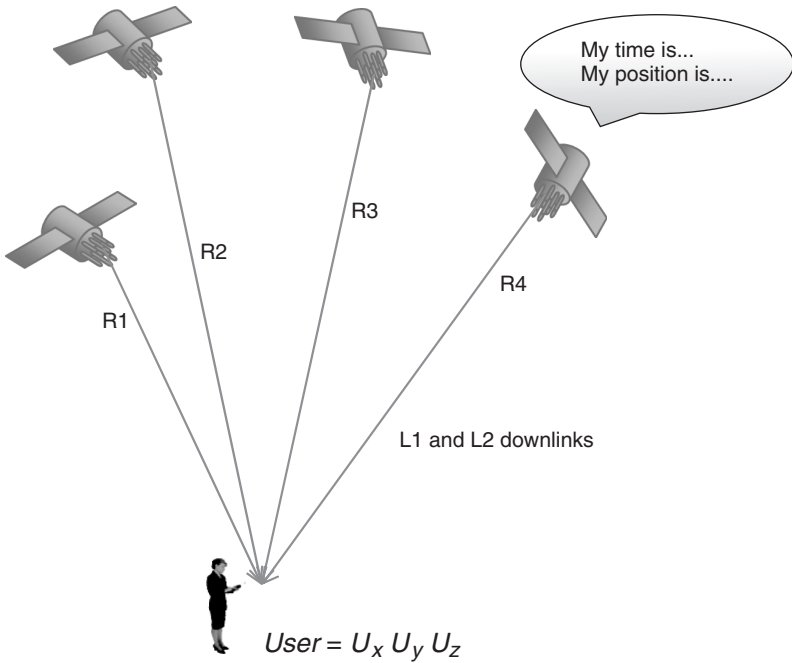


Figure 1.3 Sketch of four-satellite fix.

by the transmitted orbital correction data, and the user terminal position (u_x, u_y, u_z) is

$$(x_1 - u_x)^2 + (y_1 - u_y)^2 + (z_1 - u_z)^2 = (R'_1 - C_B)^2 \quad (1.4)$$

The corresponding equations for the remaining three satellites are

$$\begin{aligned} (x_2 - u_x)^2 + (y_2 - u_y)^2 + (z_2 - u_z)^2 &= (R'_2 - C_B)^2 \\ (x_3 - u_x)^2 + (y_3 - u_y)^2 + (z_3 - u_z)^2 &= (R'_3 - C_B)^2 \\ (x_4 - u_x)^2 + (y_4 - u_y)^2 + (z_4 - u_z)^2 &= (R'_4 - C_B)^2 \end{aligned} \quad (1.5)$$

Equations 1.4 and 1.5 constitute four equations in four unknowns (u_x, u_y, u_z, C_B) and so enable the user terminal location to be determined.

In a similar way the user terminal's velocity can be determined by measuring the Doppler shift of the received carrier frequency of the signal from each of the four satellites. As in the case of time, an error due to the offset of the

receiver oscillator frequency with GPS time can be removed using a four-satellite measurement. A set of equations with the three velocity components plus this offset again gives four equations with four unknowns (V_x , V_y , V_z and the user oscillator offset).

1.3 Operation of GPS

In this section we will take the basic concept described above and describe how a practical system (NAVSTAR GPS) can be implemented. As explained above, the user must be able to see four satellites simultaneously to get a fix, so the concept of a constellation of MEO satellites (altitude 20 183 km) with 12 h circular orbits inclined at 55° to the equator in six orbital planes was conceived [3]. With four satellites per orbital plane the operational constellation is 24 satellites (Figure 1.2); in 2010 the constellation had risen to 32 satellites. Figure 1.4 shows the satellite trajectories as viewed from the Earth for two orbits (24 hours) with one satellite's orbit shown by the heavy line for clarity.

This pattern repeats every day, although a given satellite in a given place is seen four minutes earlier each day. Assuming an open (non-urban) environment, the four 'seen' satellites need to be above a 15° elevation angle in order to avoid problems with multipath propagation. As we can see from Figure 1.5, this can be achieved at all points on the Earth's surface, even at the poles.

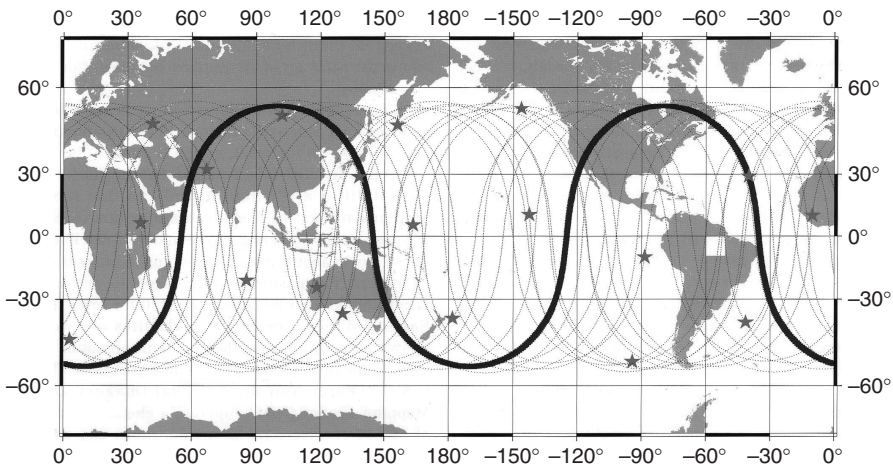


Figure 1.4 Satellite trajectories as viewed from Earth for two orbits (24 hours) with one satellite's orbit emphasised for clarity [5].

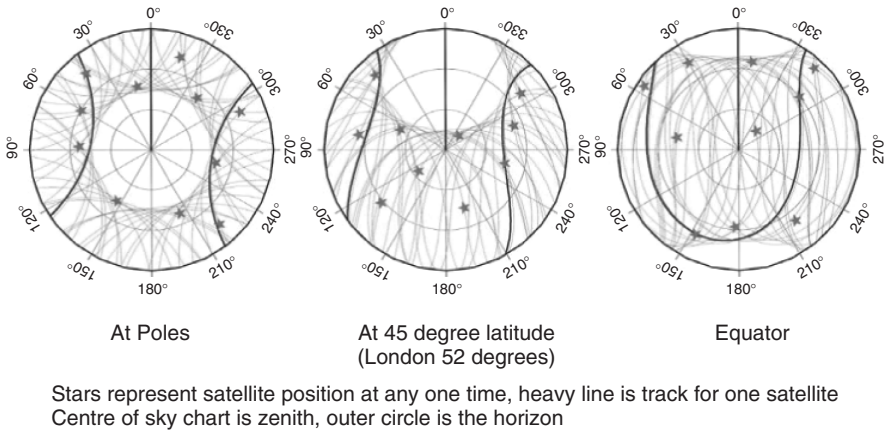


Figure 1.5 View of constellation from a user [5].

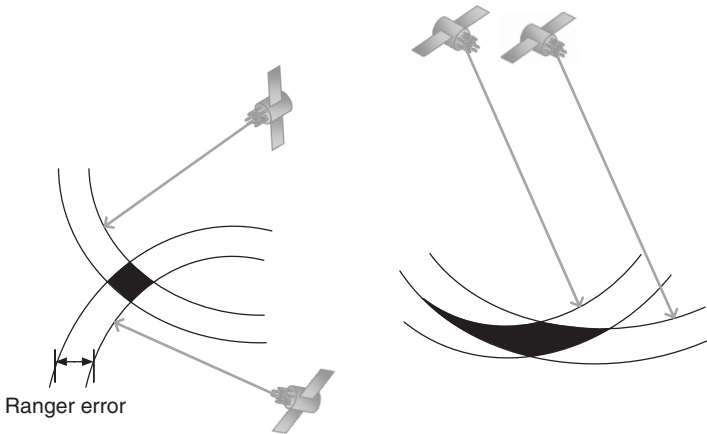


Figure 1.6 A 2D representation of range error as a function of satellite relative position (Shaded area represents region of position uncertainty).

Careful choice of location of the four satellites used for a fix can help accuracy, as can be simply illustrated in the 2D navigation system shown in Figure 1.6 and termed *dilution of precision*. The concept is of course extendable to the full 3D constellation of GPS.

GPS time is maintained on board the satellites by using a caesium and pair of rubidium atomic clocks providing an accuracy of better than 1 ns, which is improved by passing onto the user the clock adjustments determined by