GPS Basics

Introduction to the system
Application overview

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Author:	Jean-Marie Zogg
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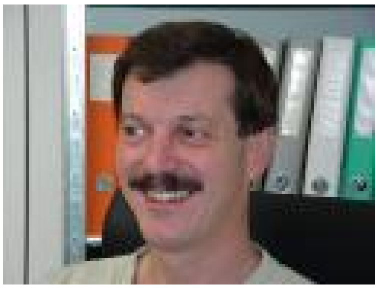
u-blox ag
Zuercherstrasse 68
CH-8800 Thalwil
Switzerland

Phone: +41 1 722 74 44
Fax: +41 1 722 74 47

Internet: www.u-blox.com

Preface by the author



Jean-Marie Zogg

My Way

In 1990, I was travelling by train from Chur to Brig in the Swiss canton of Valais. In order to pass the time during the journey, I had brought a few trade journals with me. Whilst thumbing through an American publication, I came across a specialist article about satellites that described a new positioning and navigational system. Using a few US satellites, this particular system, known as a Global Positioning System or GPS, was able to determine a position anywhere in the world to within an accuracy of about 100m (*).

As a keen sportsman and mountain trekker, I had ended up on many an occasion in precarious situations due to a lack of local knowledge and I was therefore fascinated by the prospect of being able to determine my position in fog or at night by using a revolutionary process involving a GPS receiver. After reading the article I was smitten by the GPS bug.

I then began to delve deeper into the Global Positioning System. I aroused a lot of enthusiasm amongst students at my university for this particular use of GPS, and as a result, produced various items of course work as well as degree papers on the subject. Feeling that I was a true GPS expert, I considered myself qualified to spread the ‘navigation message’ and compiled specialist articles about GPS for various magazines and newspapers. As my specialist knowledge grew, so did my enthusiasm for the system and the degree to which I became hooked on the subject.

Why read this book?

Basically, a GPS receiver determines just four variables: longitude, latitude, height and time. Additional information (e.g. speed, direction etc.) can be derived from these four components. An appreciation of the way in which the GPS system functions is necessary, in order to develop new, fascinating applications. If one is familiar with the technical background to the GPS system, it then becomes possible to develop and use new positioning and navigational equipment. This book also describes the limitations of the system, so that people do not expect too much from it.

Before you decide to embark on this text, I would like to warn you that there is no known cure for the GPS bug and that you proceed at your own peril!

How did this book come about?

Two years ago, I decided to reduce the amount of time I spent lecturing at the university, in order to take another look at industry. My aim was to work for a company professionally involved with GPS and u-blox ag received me with open arms. The company wanted me to produce a brochure that they could give to their customers. This present synopsis is therefore the result of earlier articles and newly compiled chapters.

A heartfelt wish

I wish you every success with your work within the extensive GPS community and trust that you will successfully navigate your way through this fascinating technical field. Enjoy your read!

Jean-Marie Zogg
October 2001

(*): that was in 1990, positional data is now accurate to within about 10m!

Table of contents

1 INTRODUCTION

Using the **G**lobal **P**ositioning **S**ystem (GPS, a process used to establish a position at any point on the globe) the following two values can be determined anywhere on Earth (Figure 1):

1. One’s exact location (longitude, latitude and height co-ordinates) accurate to within a range of 20 m to approx. 1 mm.
2. The precise time (Universal Time Coordinated, UTC) accurate to within a range of 60ns to approx. 5ns.

Speed and direction of travel (course) can be derived from these co-ordinates as well as the time. The co-ordinates and time values are determined by 28 satellites orbiting the Earth.

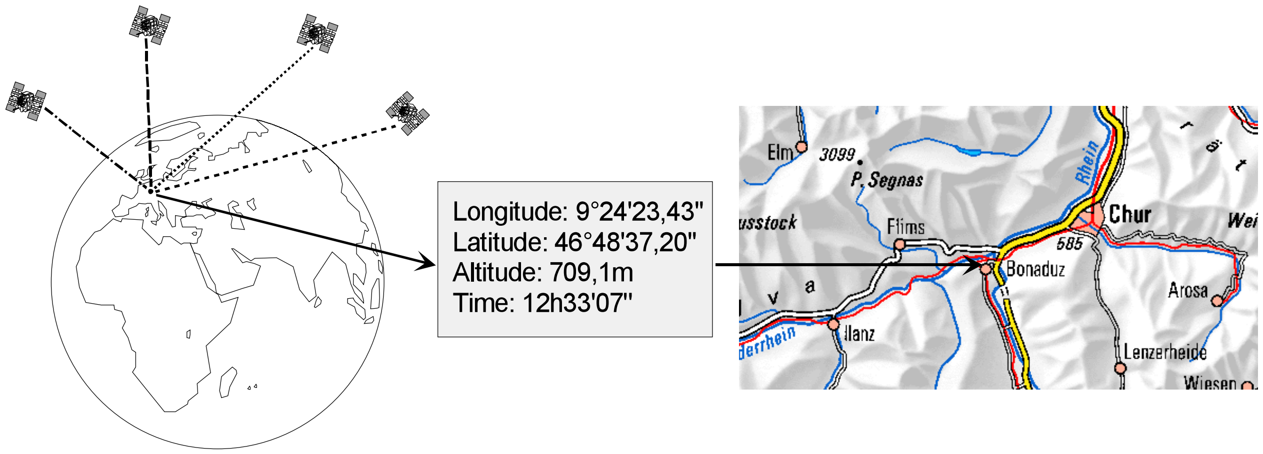


Figure 1: The basic function of GPS

GPS receivers are used for positioning, locating, navigating, surveying and determining the time and are employed both by private individuals (e.g. for leisure activities, such as trekking, balloon flights and cross-country skiing etc.) and companies (surveying, determining the time, navigation, vehicle monitoring etc.).

GPS (the full description is: **NAV**igation **S**ystem with **T**iming **A**nd **R**anging **G**lobal **P**ositioning **S**ystem, NAVSTAR-GPS) was developed by the U.S. Department of Defense (DoD) and can be used both by civilians and military personnel. The civil signal SPS (Standard Positioning Service) can be used freely by the general public, whilst the military signal PPS (Precise Positioning Service) can only be used by authorised government agencies. The first satellite was placed in orbit on 22nd February 1978, and there are currently 28 operational satellites orbiting the Earth at a height of 20,180 km on 6 different orbital planes. Their orbits are inclined at 55° to the equator, ensuring that a least 4 satellites are in radio communication with any point on the planet. Each satellite orbits the Earth in approximately 12 hours and has four atomic clocks on board.

During the development of the GPS system, particular emphasis was placed on the following three aspects:

1. It had to provide users with the capability of determining position, speed and time, whether in motion or at rest.
2. It had to have a continuous, global, 3-dimensional positioning capability with a high degree of accuracy, irrespective of the weather.
3. It had to offer potential for civilian use.

The aim of this book is to provide a comprehensive overview of the way in which the GPS system functions and the applications to which it can be put. The book is structured in such a way that the reader can graduate from simple facts to more complex theory. Important aspects of GPS such as differential GPS and equipment interfaces as well as data format are discussed in separate sections. In addition, the book is designed to act as an aid in understanding the technology that goes into GPS appliances, modules and ICs. From my own experience, I know that acquiring an understanding of the various current co-ordinate systems when using GPS equipment can often be a difficult task. A separate chapter is therefore devoted to the introduction of cartography.

This book is aimed at users interested in technology, and specialists involved in GPS applications.

2 GPS MADE SIMPLE

If you would like to . . .

- understand how the distance of a lightning bolt is determined
- understand how GPS basically functions
- know how many atomic clocks are on board a GPS satellite
- know how a position on a plane is determined
- understand why there needs to be four GPS satellites to establish a position

*then **this chapter** is for you!*

2.1 The principle of measuring signal transit time

At some time or other during a stormy night you have almost certainly attempted to work out how far away you are from a flash of lightning. The distance can be established quite easily (Figure 2): distance = the time the lightning flash is perceived (start time) until the thunder is heard (stop time) multiplied by the speed of sound (approx. 330 m/s). The difference between the start and stop time is termed the transit time.

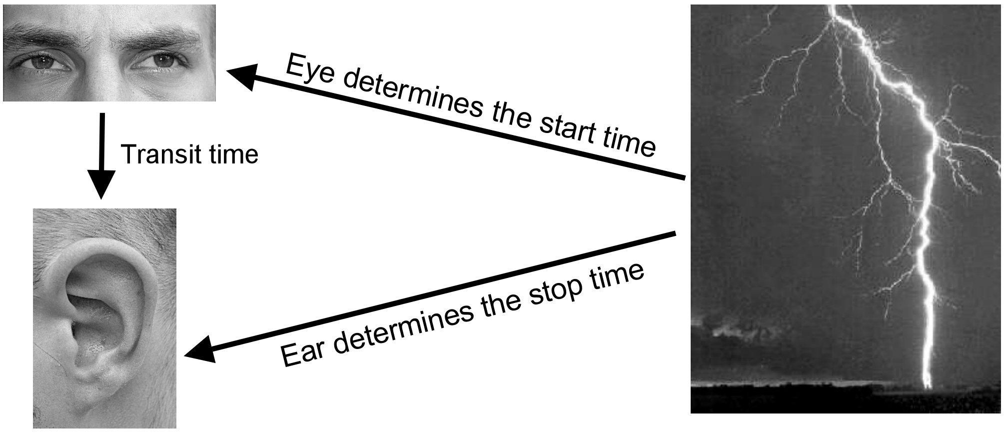


Figure 2: Determining the distance of a lightning flash

$$\text{distance} = \text{transit time} \bullet \text{the speed of sound}$$

The GPS system functions according to exactly the same principle. In order to calculate one's exact position, all that needs to be measured is the signal transit time between the point of observation and four different satellites whose positions are known.

2.1.1 Generating GPS signal transit time

28 satellites inclined at 55° to the equator orbit the Earth every 11 hours and 58 minutes at a height of 20,180 km on 6 different orbital planes (Figure 3).

Each one of these satellites has up to four atomic clocks on board. Atomic clocks are currently the most precise instruments known, losing a maximum of one second every 30,000 to 1,000,000 years. In order to make them even more accurate, they are regularly adjusted or synchronised from various control points on Earth. Each satellite transmits its exact position and its precise on board clock time to Earth at a frequency of 1575.42 MHz. These signals are transmitted at the speed of light (300,000 km/s) and therefore require approx. 67.3 ms to reach a position on the Earth's surface located directly below the satellite. The signals require a further 3.33 us for each excess kilometer of travel. If you wish to establish your position on land (or at sea or in the air), all you require is an accurate clock. By comparing the arrival time of the satellite signal with the on board clock time the moment the signal was emitted, it is possible to determine the transit time of that signal (Figure 4).

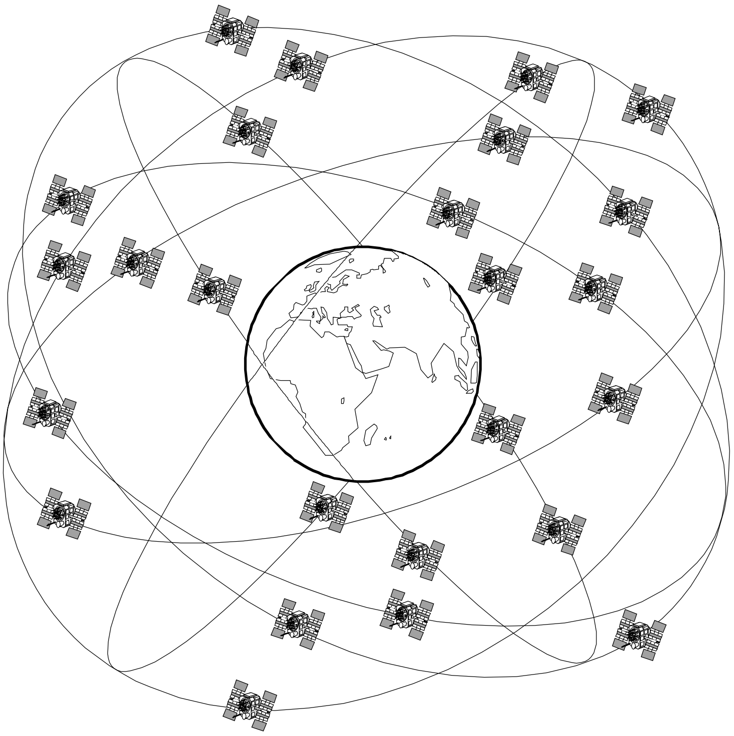


Figure 3: GPS satellites orbit the Earth on 6 orbital planes

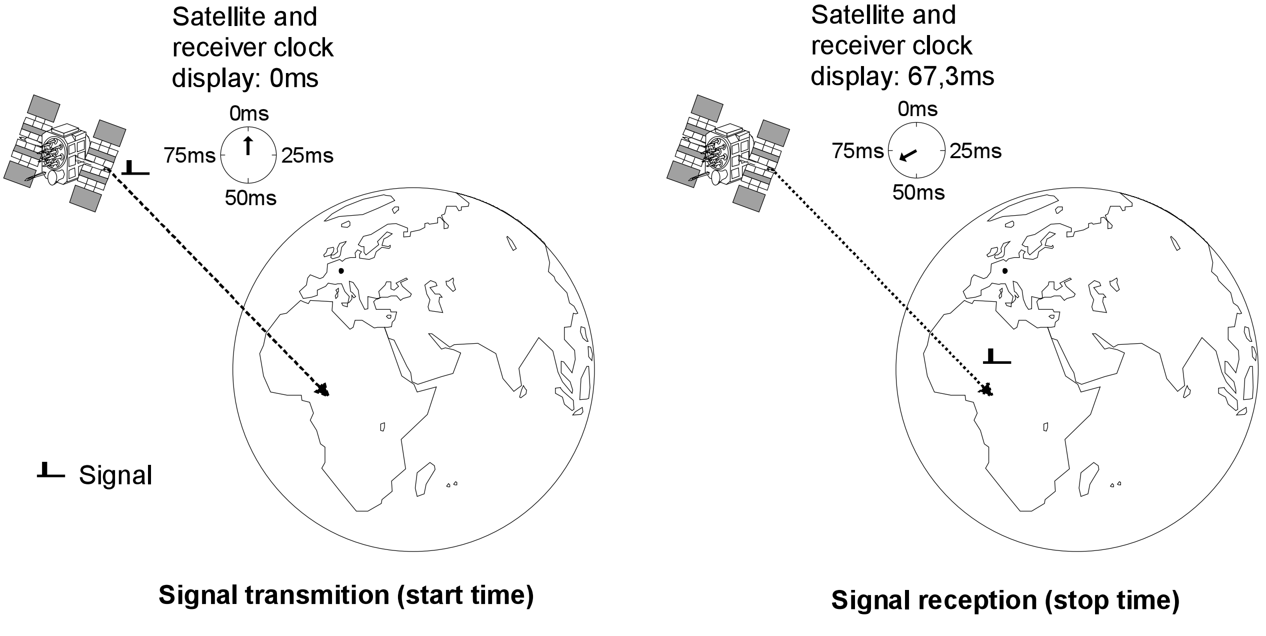


Figure 4: Determining the transit time

The distance S to the satellite can be determined by using the known transit time τ:

$$\text{distance} = \text{travel time} \bullet \text{the speed of light}$$

$$S = \tau \bullet c$$

Measuring signal transit time and knowing the distance to a satellite is still not enough to calculate one's own position in 3-D space. To achieve this, four independent transit time measurements are required. It is for this reason that signal communication with four different satellites is needed to calculate one's exact position. Why this should be so, can best be explained by initially determining one's position on a plane.

2.1.2 Determining a position on a plane

Imagine that you are wandering across a vast plateau and would like to know where you are. Two satellites are orbiting far above you transmitting their own on board clock times and positions. By using the signal transit time to both satellites you can draw two circles with the radii S1 and S2 around the satellites. Each radius corresponds to the distance calculated to the satellite. All possible distances to the satellite are located on the circumference of the circle. If the position above the satellites is excluded, the location of the receiver is at the exact point where the two circles intersect beneath the satellites (Figure 5),

Two satellites are sufficient to determine a position on the X/Y plane.

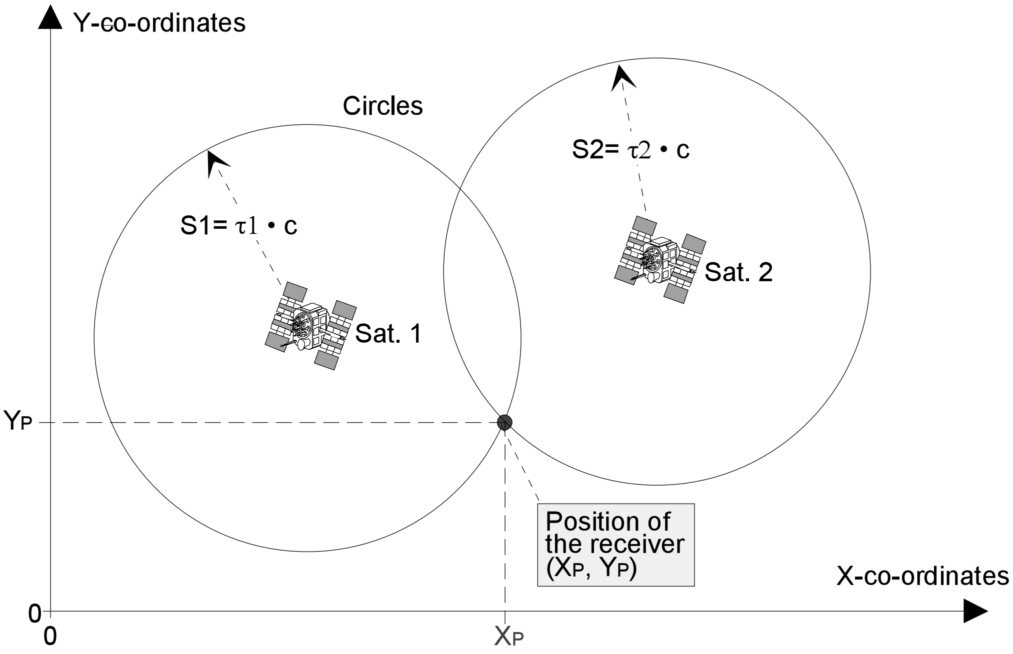


Figure 5: The position of the receiver at the intersection of the two circles

In reality, a position has to be determined in three-dimensional space, rather than on a plane. As the difference between a plane and three-dimensional space consists of an extra dimension (height Z), an additional third satellite must be available to determine the true position. If the distance to the three satellites is known, all possible positions are located on the surface of three spheres whose radii correspond to the distance calculated. The position sought is at the point where all three surfaces of the spheres intersect (Figure 6).

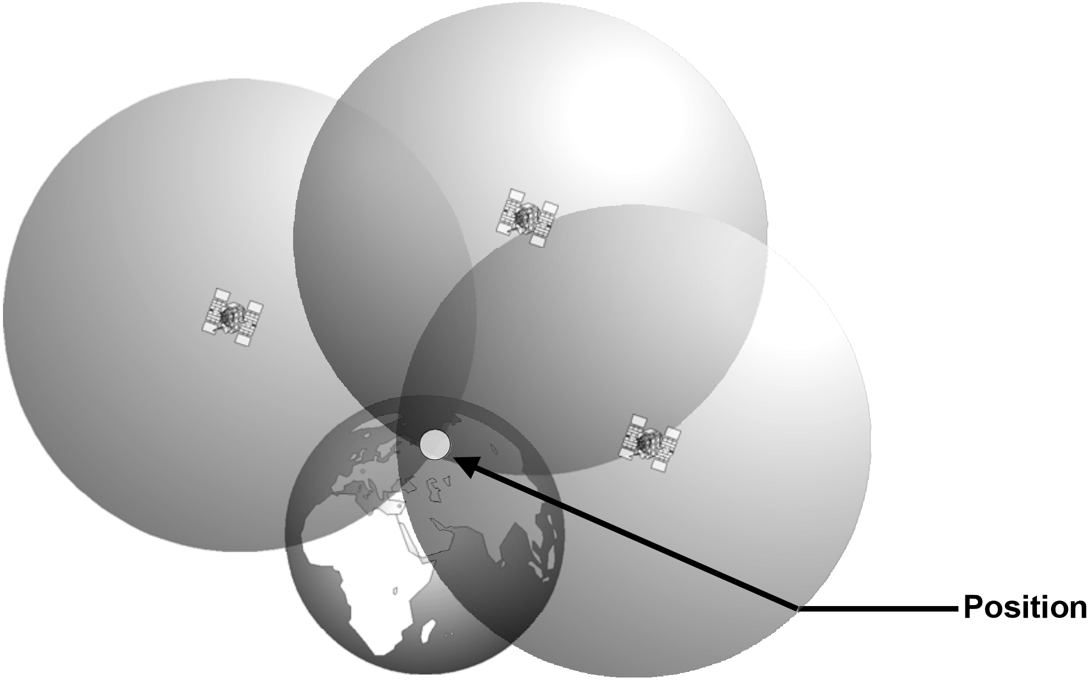


Figure 6: The position is determined at the point where all three spheres intersect

All statements made so far will only be valid, if the terrestrial clock and the atomic clocks on board the satellites are synchronised, i.e. signal transit time can be correctly determined.

2.1.3 The effect and correction of time error

We have been assuming up until now that it has been possible to measure signal transit time precisely. However, this is not the case. For the receiver to measure time precisely a highly accurate, synchronised clock is needed. If the transit time is out by just 1 µs this produces a positional error of 300m. As the clocks on board all three satellites are synchronised, the transit time in the case of all three measurements is inaccurate by the same amount. Mathematics is the only thing that can help us now. We are reminded when producing calculations that if N variables are unknown, we need N independent equations.

If the time measurement is accompanied by a constant unknown error, we will have four unknown variables in 3-D space:

- longitude (X)
- latitude (Y)
- height (Z)
- time error (Δt)

It therefore follows that in three-dimensional space four satellites are needed to determine a position.

2.1.4 Determining a position in 3-D space

In order to determine these four unknown variables, four independent equations are needed. The four transit times required are supplied by the four different satellites (sat. 1 to sat. 4). The 28 GPS satellites are distributed around the globe in such a way that at least 4 of them are always "visible" from any point on Earth (Figure 7).

Despite receiver time errors, a position on a plane can be calculated to within approx. 5 – 10 m.

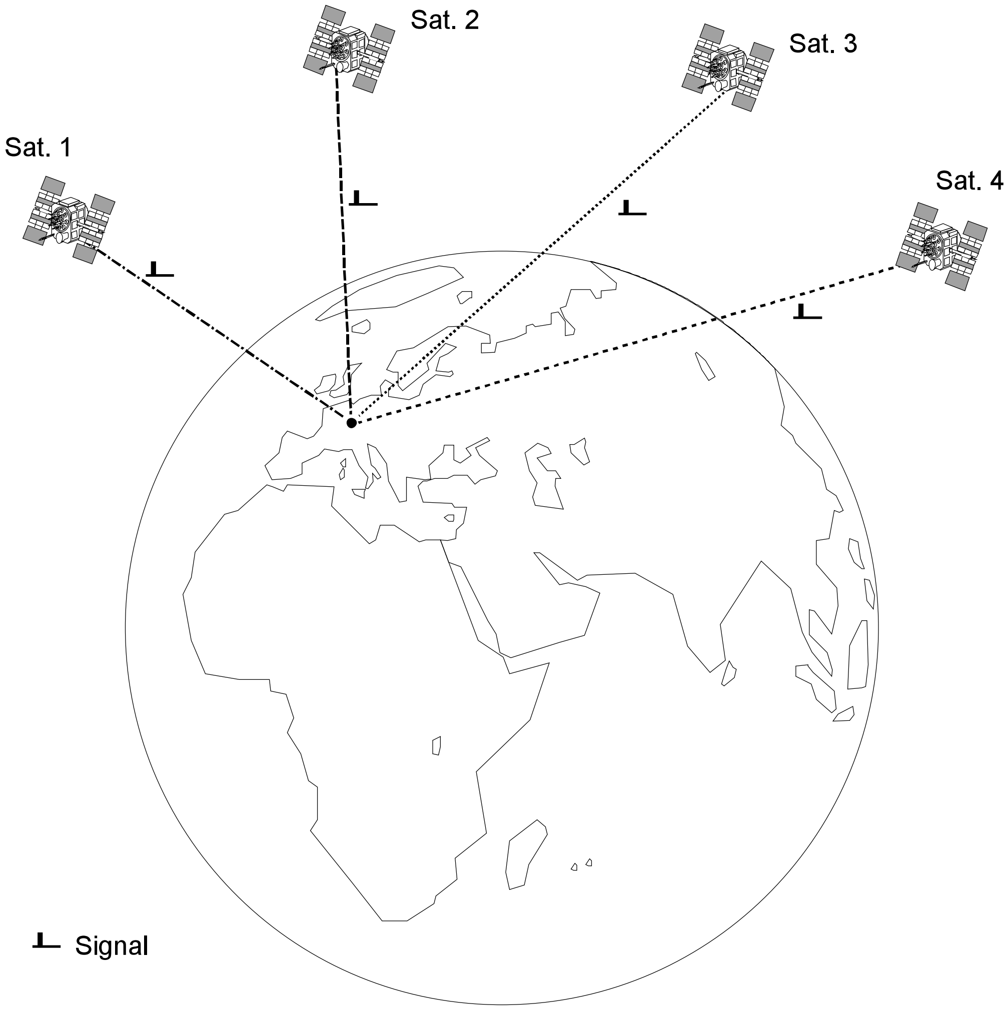


Figure 7: Four satellites are required to determine a position in 3-D space.

3 GPS, THE TECHNOLOGY

If you would like to . . .

- understand why three different GPS segments are needed
- know what function each individual segment has
- know how a GPS satellite is basically constructed
- know what sort of information is relayed to Earth
- understand how a satellite signal is generated
- understand how GPS signal transit time is determined
- understand what correlation means

*then **this chapter** is for you!*

3.1 Description of the entire system

The Global Positioning System (GPS) comprises three segments (Figure 8):

- The space segment (all functional satellites)
- The control segment (all ground stations involved in the monitoring of the system: master control station, monitor stations, and ground control stations)
- The user segment (all civil and military GPS users)

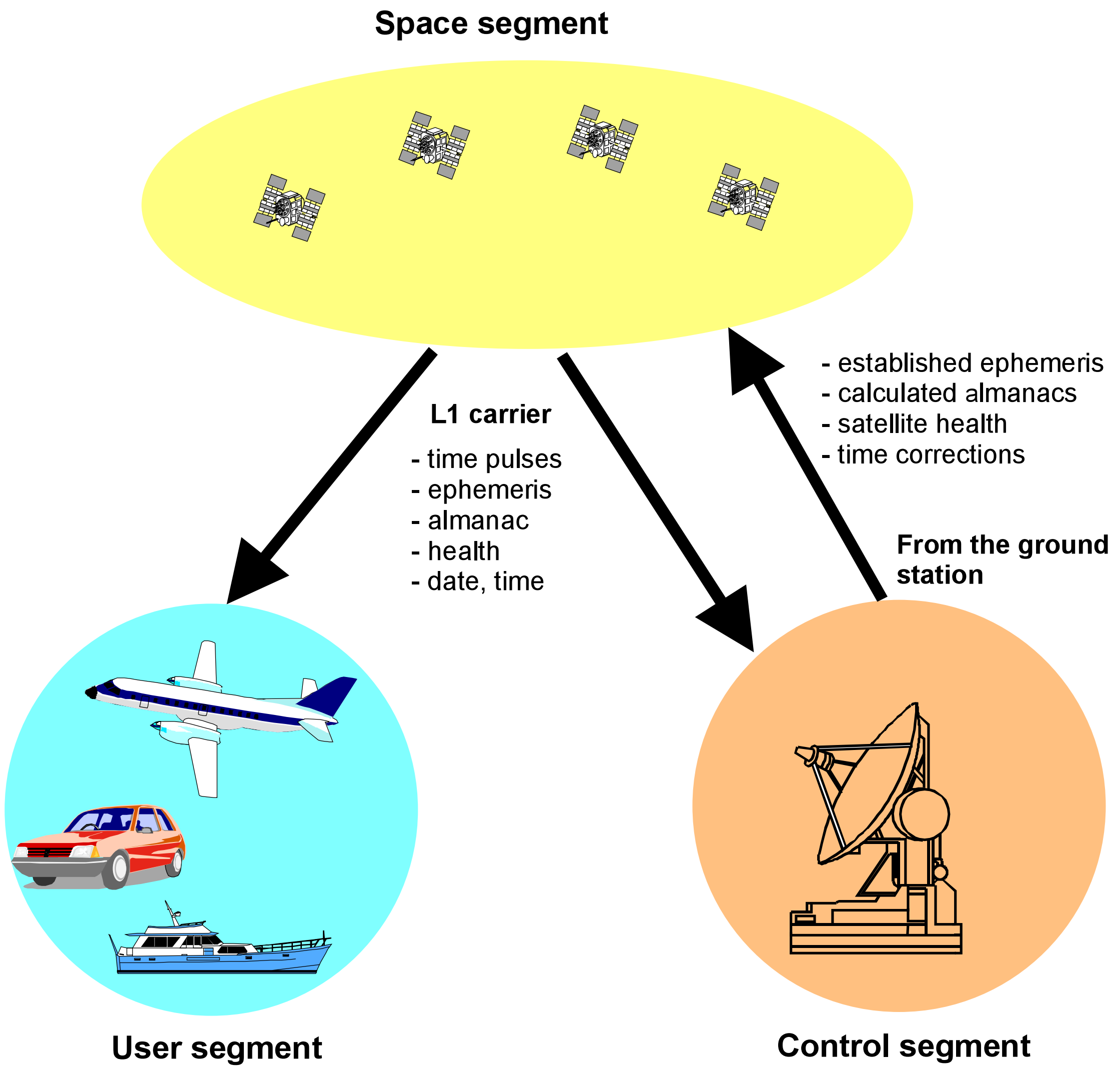


Figure 8: The three GPS segments

As can be seen in Figure 8 there is unidirectional communication between the space segment and the user segment. The three ground control stations are equipped with ground antennae, which enable bidirectional communication.

3.2 Space segment

3.2.1 Satellite movement

The space segment currently consists of 28 operational satellites (Figure 3) orbiting the Earth on 6 different orbital planes (four to five satellites per plane). They orbit at a height of 20,180 km above the Earth's surface and are inclined at 55° to the equator. Any one satellite completes its orbit in around 12 hours. Due to the rotation of the Earth, a satellite will be at its initial starting position (Figure 9) after approx. 24 hours (23 hours 56 minutes to be precise).

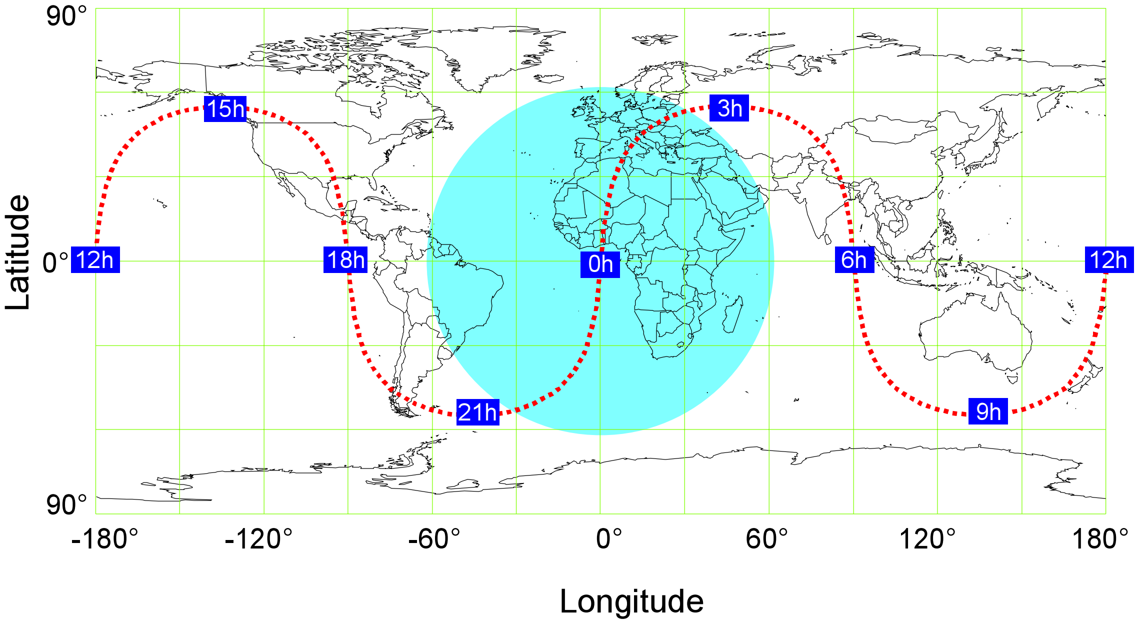


Figure 9: Position of the 28 GPS satellites at 12.00 hrs UTC on 14th April 2001

Satellite signals can be received anywhere within a satellite's effective range. Figure 9 shows the effective range (shaded area) of a satellite located directly above the equator/zero meridian intersection.

The distribution of the 28 satellites at any given time can be seen in Figure 10. It is due to this ingenious pattern of distribution and to the great height at which they orbit that communication with at least 4 satellites is ensured at all times anywhere in the world.

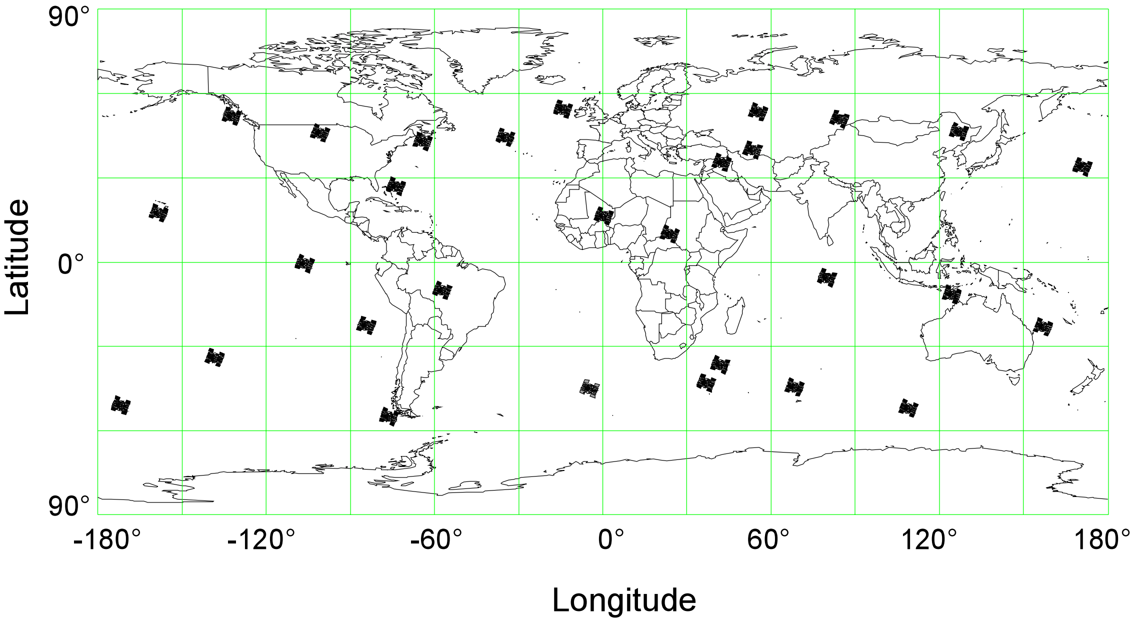


Figure 10: Position of the 28 GPS satellites at 12.00 hrs UTC on 14th April 2001

3.2.2 The GPS satellites

3.2.2.1 Construction of a satellite

All 28 satellites transmit time signals and data synchronised by on board atomic clocks at the same frequency (1575.42 MHz). The minimum signal strength received on Earth is approx. -158dBW to -160dBW [i]. In accordance with the specification, the maximum strength is approx. -153dBW.

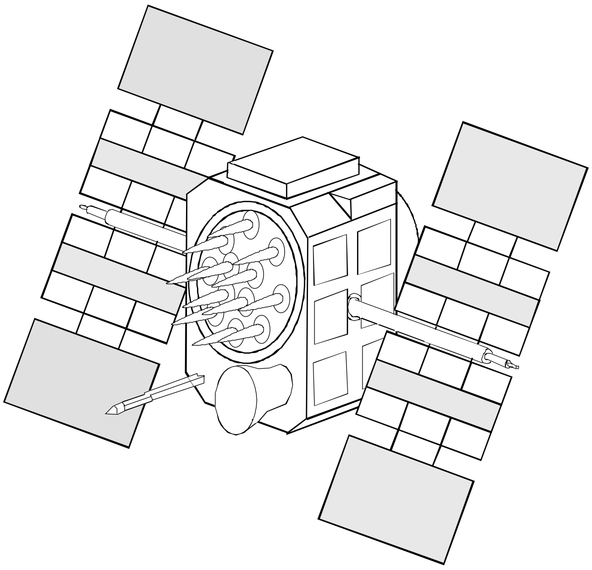


Figure 11: A GPS satellite

3.2.2.2 The communication link budget analysis

The link budget analysis (Table 1) between a satellite and a user is suitable for establishing the required level of satellite transmission power. In accordance with the specification, the minimum amount of power received must not fall below –160dBW (-130dBm). In order to ensure this level is maintained, the satellite L1 carrier transmission power, modulated with the C/A code, must be 21.9W.

	Gain (+) /loss (-)	Absolute value
Power at the satellite transmitter		13.4dBW (43.4dBm=21.9W)
Satellite antenna gain (due to concentration of the signal at 14.3°)	+13.4dB	
Radiate power EIRP (Effective Integrated Radiate Power)		26.8dBW (56.8dBm)
Loss due to polarisation mismatch	-3.4dB	
Signal attenuation in space	-184.4dB	
Signal attenuation in the atmosphere	-2.0dB	
Gain from the reception antenna	+3.0dB	
Power at receiver input		-160dBW (-130dBm=100.0*10^{-18}W)

Table 1: L1 carrier link budget analysis modulated with the C/A code

The received power of –160dBW is unimaginably small. The maximum power density is 14.9 dB below receiver background noise [ii].

3.2.2.3 Satellite signals

The following information (navigation message) is transmitted by the satellite at a rate of 50 bits per second [iii]:

- Satellite time and synchronisation signals
- Precise orbital data (ephemeris)
- Time correction information to determine the exact satellite time
- Approximate orbital data for all satellites (almanac)
- Correction signals to calculate signal transit time
- Data on the ionosphere
- Information on satellite health

The time required to transmit all this information is 12.5 minutes. By using the navigation message the receiver is able to determine the transmission time of each satellite signal and the exact position of the satellite at the time of transmission.

Each of the 28 satellites transmits a unique signature assigned to it. This signature consists of an apparent random sequence (Pseudo Random Noise Code, PRN) of 1023 zeros and ones (Figure 12).

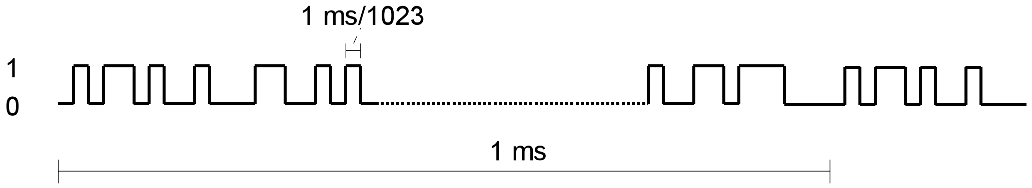


Figure 12: Pseudo Random Noise

Lasting a millisecond, this unique identifier is continually repeated and serves two purposes with regard to the receiver:

- Identification: the unique signature pattern means that the receiver knows from which satellite the signal originated.
- Signal transit time measurement

3.2.3 Generating the satellite signal

3.2.3.1 Simplified block diagram

On board the satellites are four highly accurate atomic clocks. The following time pulses and frequencies required for day-to-day operation are derived from the resonant frequency of one of the four atomic clocks (figs. 13 and 14):

- The 50 Hz data pulse
- The C/A code pulse (Coarse/Acquisition code, PRN-Code, coarse reception code at a frequency of 1023 MHz), which modulates the data using an exclusive-or operation (this spreads the data over a 1MHz bandwidth)
- The frequency of the civil L1 carrier (1575.42 MHz)

The data modulated by the C/A code modulates the L1 carrier in turn by using Bi-Phase-Shift-Keying (BPSK). With every change in the modulated data there is a 180° change in the L1 carrier phase.

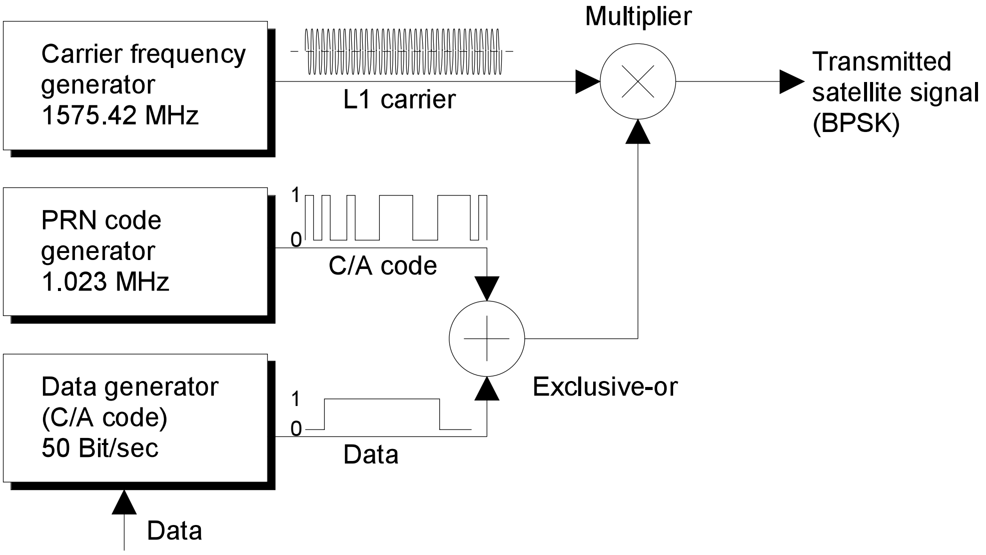


Figure 13: Simplified satellite block diagram

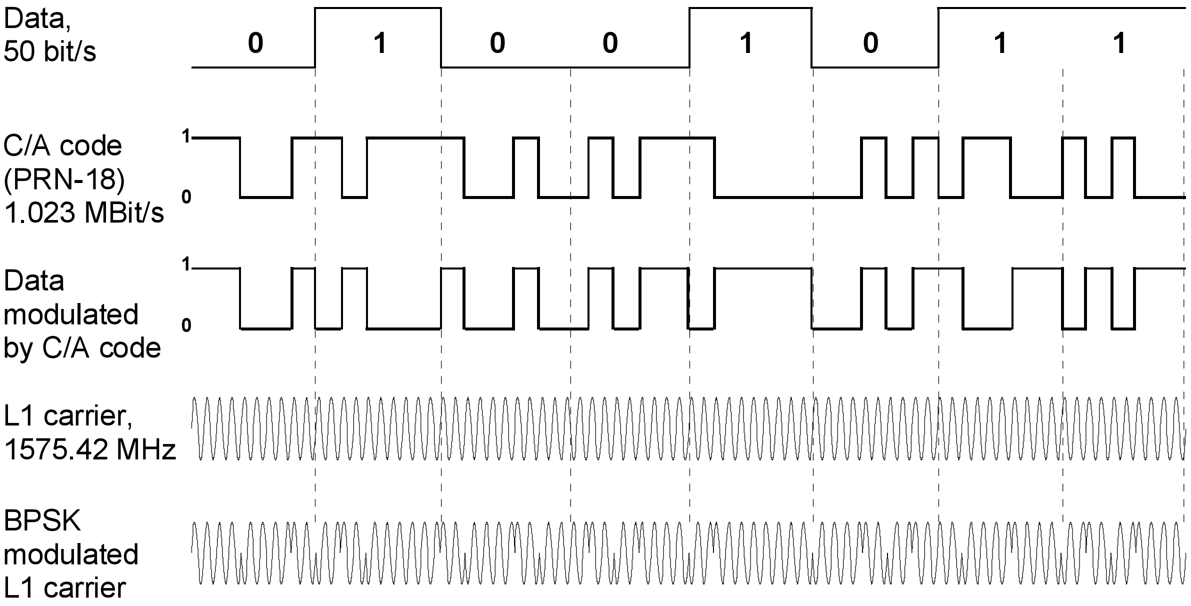


Figure 14: Data structure of a GPS satellite

3.2.3.2 Detailed block system

The atomic clocks on board a satellite have a stability greater than 2.10^{-13} [iv]. The basic frequency of 10.23MHz is derived in a satellite from the resonant frequency of one of the four atomic clocks. In turn, the carrier frequency, data frequency, the timing for the generation of pseudo random noise (PRN), and the C/A code (course / acquisition code), are derived from this basic frequency (Figure 15). As all 28 satellites transmit on 1575.42 MHz, a process known as CDMA Multiplex (Code Division Multiple Access) is used. The data is transmitted based on DSSS modulation (Direct Sequence Spread Spectrum Modulation) [v]. The C/A code generator has a frequency of 1023 MHz and a period of 1,023 chips, which corresponds to a millisecond. The C/A code used (PRN code), which is the same as a gold code, and therefore exhibits good correlation properties, is generated by a feedback shift register.

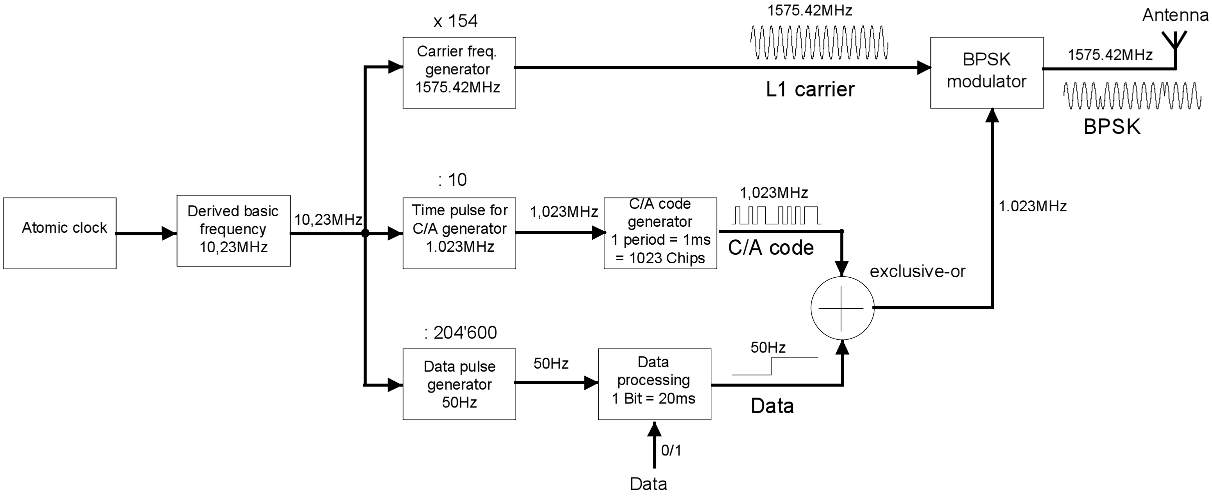


Figure 15: Detailed block system of a GPS satellite

The modulation process described above is referred to as DSSS modulation (Direct Sequence Spread Modulation), the C/A code playing an important part in this process. As all satellites transmit on the same frequency (1575.42 MHz), the C/A code contains the identification and information generated by each individual satellite. The C/A code is an apparent random sequence of 1023 bits known as pseudo random noise (PRN). This signature, which lasts a millisecond and is unique to each satellite, is constantly repeated. A satellite is always identified, therefore, by its corresponding C/A code.

3.3 Control segment

The control segment (Operational Control System OCS) consists of a Master Control Station located in the state of Colorado, five monitor stations equipped with atomic clocks that are spread around the globe in the vicinity of the equator, and three ground control stations that transmit information to the satellites.

The most important tasks of the control segment are:

- Observing the movement of the satellites and computing orbital data (ephemeris)
- Monitoring the satellite clocks and predicting their behaviour
- Synchronising on board satellite time
- Relaying precise orbital data received from satellites in communication
- Relaying the approximate orbital data of all satellites (almanac)
- Relaying further information, including satellite health, clock errors etc.

The control segment also oversees the artificial distortion of signals (SA, Selective Availability), in order to degrade the system's positional accuracy for civil use. System accuracy had been intentionally degraded up until May 2000 for political and tactical reasons by the U.S. Department of Defense (DoD), the satellite operators. It was shut down in May 2000, but it can be started up again, if necessary, either on a global or regional basis.

3.4 User segment

The signals transmitted by the satellites take approx. 67 milliseconds to reach a receiver. As the signals travel at the speed of light, their transit time depends on the distance between the satellites and the user.

Four different signals are generated in the receiver having the same structure as those received from the 4 satellites. By synchronising the signals generated in the receiver with those from the satellites, the four satellite signal time shifts Δt are measured as a timing mark (Figure 16). The measured time shifts Δt of all 4 satellite signals are used to determine signal transit time.

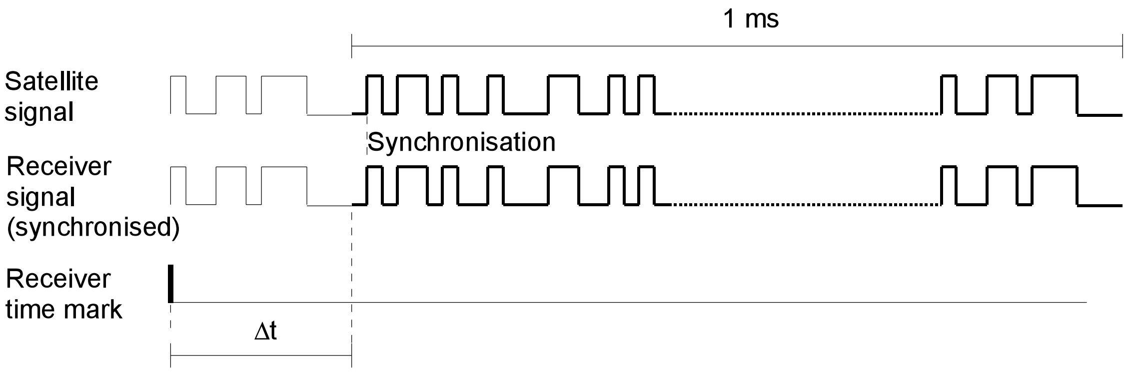


Figure 16: Measuring signal transit time

In order to determine the position of a user, radio communication with four different satellites is required. The relevant distance to the satellites is determined by the transit time of the signals. The receiver then calculates the user's latitude φ, longitude λ, height h and time t from the range and known position of the four satellites. Expressed in mathematical terms, this means that the four unknown variables φ, λ, h and t are determined from the distance and known position of these four satellites, although a fairly complex level of iteration is required, which will be dealt with in greater detail at a later stage.

As mentioned earlier, all 28 satellites transmit on the same frequency, but with a different C/A code. This process is basically termed Code Division Multiple Access (CDMA). Signal recovery and the identification of the satellites takes place by means of correlation. As the receiver is able to recognise all C/A codes currently in use, by systematically shifting and comparing every code with all incoming satellite signals, a complete match will eventually occur (that is to say that the correlation factor CF is one), and a correlation point will be attained (Figure 17). The correlation point is used to measure the actual signal transit time and, as previously mentioned, to identify the satellite.

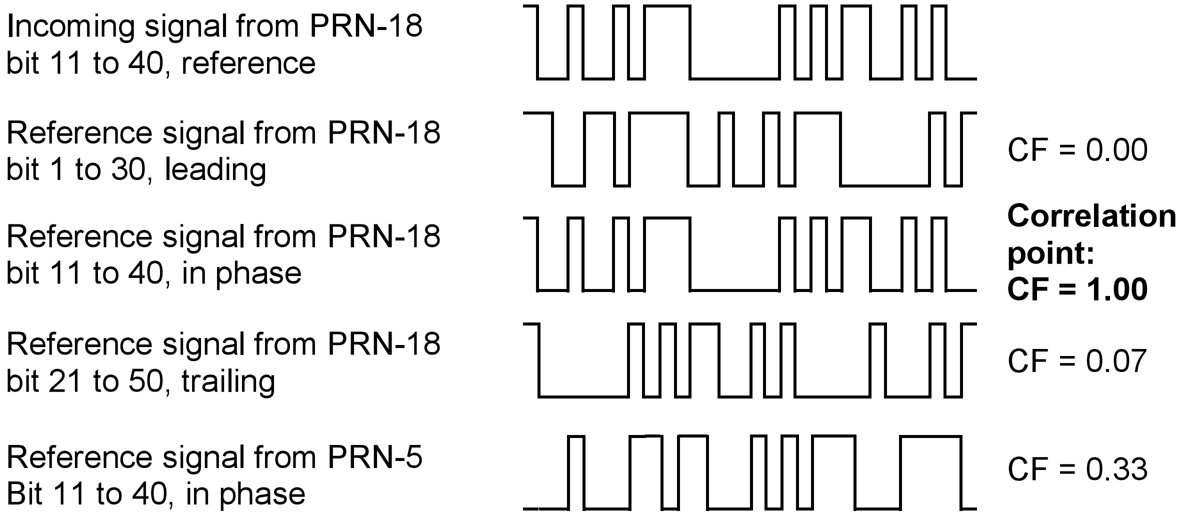


Figure 17: Demonstration of the correction process across 30 bits

The quality of the correlation is expressed here as CF (correlation factor). The value range of CF lies between minus one and plus one and is only plus one when both signals completely match (bit sequence and phase).

$$CF = \frac{1}{N} \bullet \sum_{i=1}^{N} \left[(\mathrm{mB}) - (\mathrm{uB}) \right]$$

mB: number of all matched bits
uB: number of all unmatched bits
N: number of observed bits.

4 THE GPS NAVIGATION MESSAGE

If you would like to . . .

- know what information is transmitted to Earth by GPS satellites
- understand why a minimum period of time is required to for the GPS system to come on line
- know what data can be called up where
- know what frames and subframes are
- understand why the same data is transmitted with varying degrees of accuracy

then ***this chapter*** *is for you!*

4.1 Introduction

The navigation message [vi] is a continuous stream of data transmitted at 50 bits per second. Each satellite relays the following information to Earth:

- System time and clock correction values
- Its own highly accurate orbital data (ephemeris)
- Approximate orbital data for all other satellites (almanac)
- System health, etc.

The navigation message is needed to calculate the current position of the satellites and to determine signal transit times.

The data stream is modulated to the HF carrier wave of each individual satellite. Data is transmitted in logically grouped units known as frames or pages. Each frame is 1500 bits long and takes 30 seconds to transmit. The frames are divided into 5 subframes. Each subframe is 300 bits long and takes 6 seconds to transmit. In order to transmit a complete almanac, 25 different frames are required (called pages). Transmission time for the entire almanac is therefore 12.5 minutes. A GPS receiver must have collected the complete almanac at least once to be capable of functioning (e.g. for its primary initialisation).

4.2 Structure of the navigation message

A frame is 1500 bits long and takes 30 seconds to transmit. The 1500 bits are divided into five subframes each of 300 bits (duration of transmission 6 seconds). Each subframe is in turn divided into 10 words each containing 30 bits. Each subframe begins with a telemetry word and a handover word (HOW). A complete navigation message consists of 25 frames (pages). The structure of the navigation message is illustrated in diagrammatic format in Figure 18.

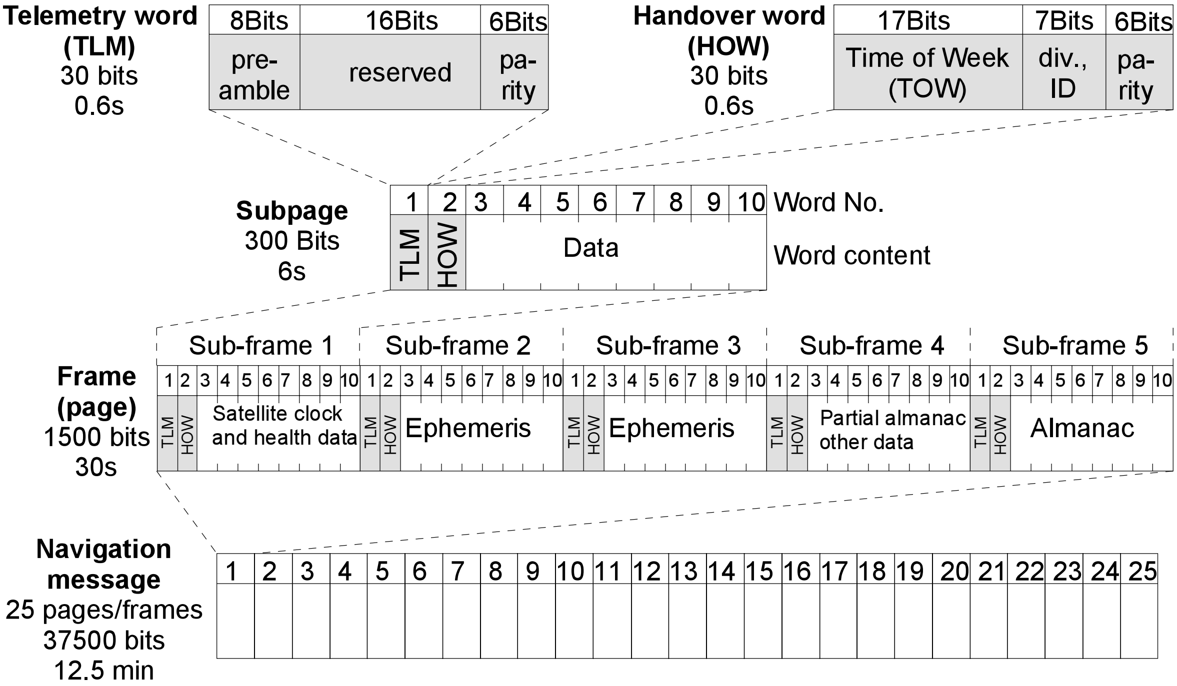


Figure 18: Structure of the entire navigation message

4.2.1 Information contained in the subframes

A frame is divided into five subframes, each subframe transmitting different information.

- Subframe 1 contains the time values of the transmitting satellite, including the parameters for correcting signal transit delay and on board clock time, as well as information on satellite health and an estimation of the positional accuracy of the satellite. Subframe 1 also transmits the so-called 10-bit week number (a range of values from 0 to 1023 can be represented by 10 bits). GPS time began on Sunday, 6th January 1980 at 00:00:00 hours. Every 1024 weeks the week number restarts at 0.
- Subframes 2 and 3 contain the ephemeris data of the transmitting satellite. This data provides extremely accurate information on the satellite's orbit.
- Subframe 4 contains the almanac data on satellite numbers 25 to 32 (N.B. each subframe can transmit data from one satellite only), the difference between GPS and UTC time and information regarding any measurement errors caused by the ionosphere.
- Subframe 5 contains the almanac data on satellite numbers 1 to 24 (N.B. each subframe can transmit data from one satellite only). All 25 pages are transmitted together with information on the health of satellite numbers 1 to 24.

4.2.2 TLM and HOW

The first word of every single frame, the telemetry word (TLM), contains a preamble sequence 8 bits in length (10001011) used for synchronization purposes, followed by 16 bits reserved for authorized users. As with all words, the final 6 bits of the telemetry word are parity bits.

The handover word (HOW) immediately follows the telemetry word in each subframe. The handover word is 17 bits in length (a range of values from 0 to 131071 can be represented using 17 bits) and contains within its structure the start time for the next subframe, which is transmitted as time of the week (TOW). The TOW count begins with the value 0 at the beginning of the GPS week (transition period from Saturday 23:59:59 hours to Sunday 00:00:00 hours) and is increased by a value of 1 every 6 seconds. As there are 604,800 seconds in a week, the count runs from 0 to 100,799, before returning to 0. A marker is introduced into the data stream every 6 seconds and the HOW transmitted, in order to allow synchronisation with the P code. Bit Nos. 20 to 22 are used in the handover word to identify the subframe just transmitted.

4.2.3 Subdivision of the 25 pages

A complete navigation message requires 25 pages and lasts 12.5 minutes. A page or a frame is divided into five subframes. In the case of subframes 1 to 3, the information content is the same for all 25 pages. This means that a receiver has the complete clock values and ephemeris data from the transmitting satellite every 30 seconds.

The sole difference in the case of subframes 4 and 5 is how the information transmitted is organised.

- In the case of subframe 4, pages 2, 3, 4, 5, 7, 8, 9 and 10 relay the almanac data on satellite numbers 25 to 32. In each case, the almanac data for one satellite only is transferred per page. Page 18 transmits the values for correction measurements as a result of ionospheric scintillation, as well as the difference between UTC and GPS time. Page 25 contains information on the configuration of all 32 satellites (i.e. block affiliation) and the health of satellite numbers 25 to 32.
- In the case of subframe 5, pages 1 to 24 relay the almanac data on satellite numbers 1 to 24. In each case, the almanac data for one satellite only is transferred per page. Page 25 transfers information on the health of satellite numbers 1 to 24 and the original almanac time.

4.2.4 Comparison between ephemeris and almanac data

Using both ephemeris and almanac data, the satellite orbits and therefore the relevant co-ordinates of a specific satellite can be determined at a defined point in time. The difference between the values transmitted lies mainly in the accuracy of the figures. In the following table (Table 2), a comparison is made between the two sets of figures.

Information	Ephemeris No. of bits	Almanac No. of bits
Square root of the semi major axis of orbital ellipse a	32	16
Eccentricity of orbital ellipse e	32	16

Table 2: Comparison between ephemeris and almanac data

For an explanation of the terms used in Table 2, see Figure 18.

Semi major axis of orbital ellipse: a

Eccentricity of the orbital ellipse: $e = \sqrt{\frac{a^2 - b^2}{a^2}}$

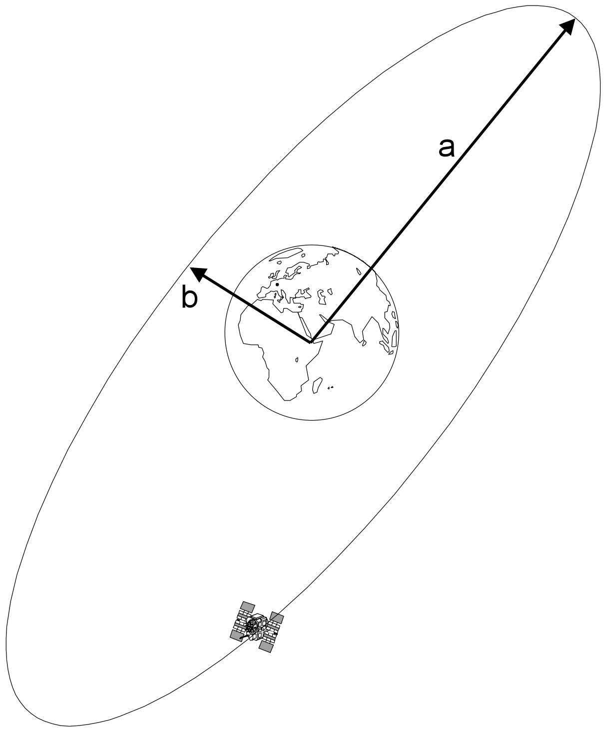


Figure 19: Ephemeris terms

5 CALCULATING POSITION

If you would like to . . .

- understand how co-ordinates and time are determined
- know what pseudo-range is
- understand why a GPS receiver must produce a position estimate at the start of a calculation
- understand how a non-linear equation is solved using four unknown variables
- know what degree of accuracy is guaranteed by the GPS system operator

*then **this chapter** is for you!*

5.1 Introduction

Although originally intended for purely military purposes, the GPS system is used today primarily for civil applications, such as surveying, navigation (air, sea and land), positioning, measuring velocity, determining time, monitoring stationary and moving objects, etc. The system operator guarantees the standard civilian user of the service that the following accuracy (Table 3) will be attained for 95% of the time (2drms value [vii]):

Horizontal accuracy	Vertical accuracy	Time accuracy
≤13 m	≤22 m	~40ns

Table 3: Accuracy of the standard civilian service

With additional effort and expenditure, e.g. several linked receivers (DGPS), longer measuring time, and special measuring techniques (phase measurement) positional accuracy can be increased to within a centimetre.

5.2 Calculating a position

5.2.1 The principle of measuring signal transit time (evaluation of pseudo-range)

In order for a GPS receiver to determine its position, it has to receive time signals from four different satellites (Sat 1 ... Sat 4), to enable it to calculate signal transit time Δt_1 ... Δt_4 (Figure 20).

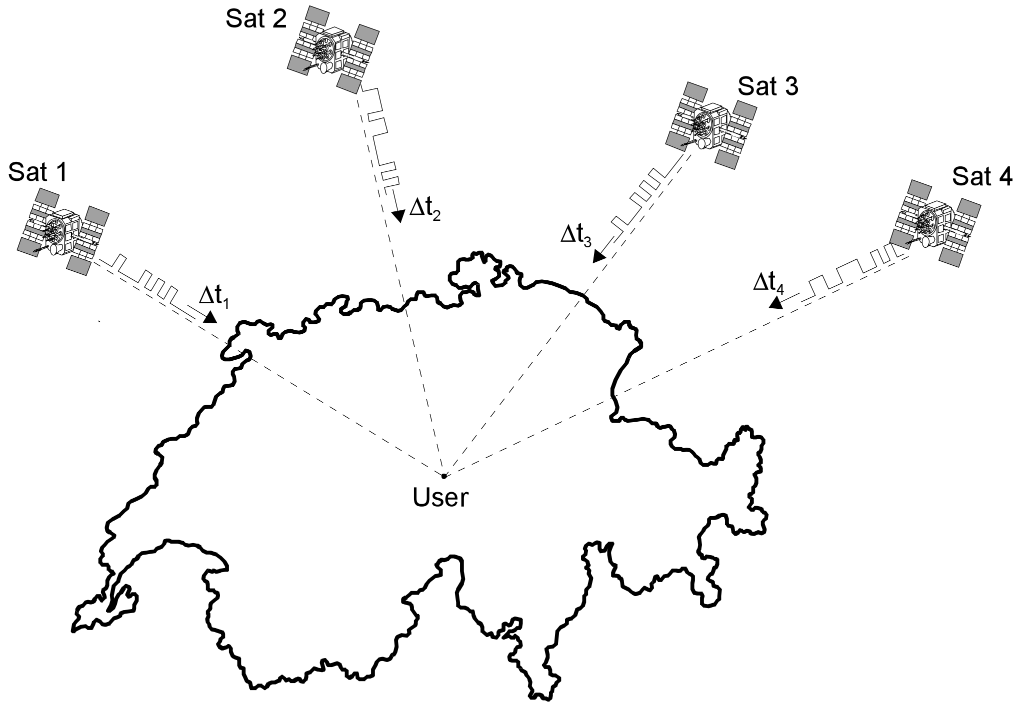


Figure 20: Four satellite signals must be received

Calculations are effected in a Cartesian, three-dimensional co-ordinate system with a geocentric origin (Figure 21). The range of the user from the four satellites R_1, R_2, R_3 and R_4 can be determined with the help of signal transit times Δt_1, Δt_2, Δt_3 and Δt_4 between the four satellites and the user. As the locations X_{Sat}, Y_{Sat} and Z_{Sat} of the four satellites are known, the user co-ordinates can be calculated.

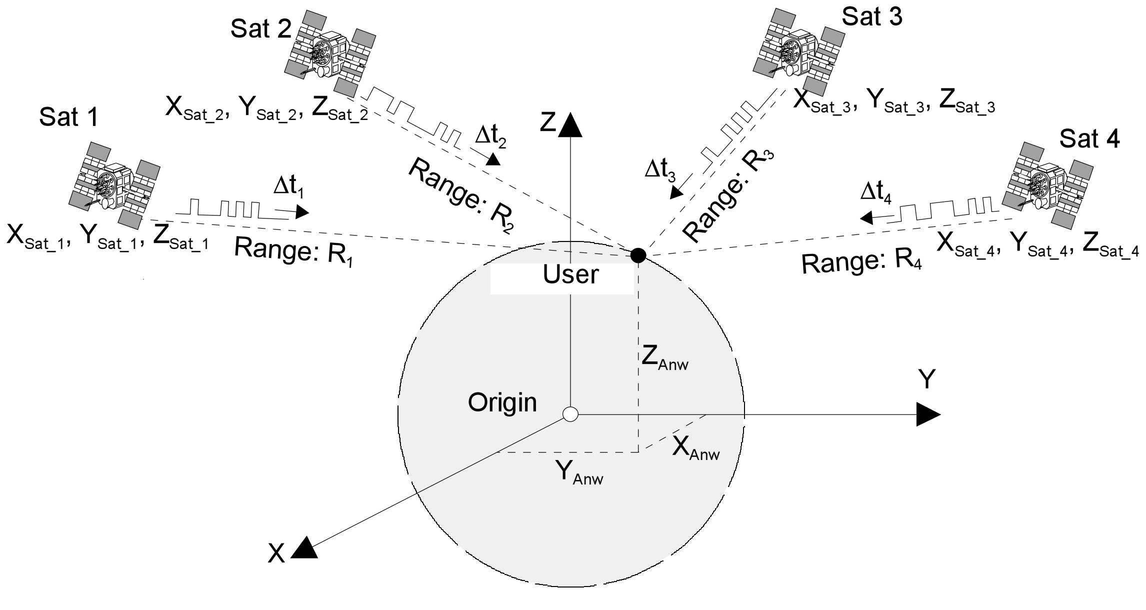


Figure 21: Three dimensional co-ordinate system

Due to the atomic clocks on board the satellites, the time at which the satellite signal is transmitted is known very precisely. All satellite clocks are adjusted or synchronised with each another and universal time co-ordinated. In contrast, the receiver clock is not synchronised to UTC and is therefore slow or fast by Δt_0. The sign Δt_0 is positive when the user clock is fast. The resultant time error Δt_0 causes inaccuracies in the measurement of signal transit time and the distance R. As a result, an incorrect distance is measured that is known as pseudo distance or pseudo-range PSR [viii].

$$\Delta t_{measured} = \Delta t + \Delta t_0 \tag{1a}$$

$$PSR = \Delta t_{measured} \cdot c = (\Delta t + \Delta t_0) \cdot c \tag{2a}$$

$$\mathrm{PSR} = \mathrm{R} + \Delta \mathrm{t}_0 \cdot \mathrm{c} \tag{3a}$$

R: true range of the satellite from the user

c: speed of light

Δt: signal transit time from the satellite to the user

Δt_0: difference between the satellite clock and the user clock

PSR: pseudo-range

The distance R from the satellite to the user can be calculated in a Cartesian system as follows:

$$R = \sqrt{(X_{Sat} - X_{User})^2 + (Y_{Sat} - Y_{User})^2 + (Z_{Sat} - Z_{User})^2} \tag{4a}$$

thus (4) into (3)

$$\mathrm{PSR} = \sqrt{(\mathrm{X}_{\mathrm{Sat}} - \mathrm{X}_{User})^2 + (\mathrm{Y}_{\mathrm{Sat}} - \mathrm{Y}_{User})^2 + (\mathrm{Z}_{\mathrm{Sat}} - \mathrm{Z}_{User})^2} + \mathrm{c} \cdot \Delta \mathrm{t}_0 \tag{5a}$$

In order to determine the four unknown variables (Δt_0 , X_{Anw}, Y_{Anw} and Z_{Anw}), four independent equations are necessary.

The following is valid for the four satellites (i = 1 ... 4):

$$\mathrm{PSR}_{\mathrm{i}} = \sqrt{(\mathrm{X}_{\mathrm{Sat\_i}} - \mathrm{X}_{User})^2 + (\mathrm{Y}_{\mathrm{Sat\_i}} - \mathrm{Y}_{User})^2 + (\mathrm{Z}_{\mathrm{Sat\_i}} - \mathrm{Z}_{User})^2} + \mathrm{c} \cdot \Delta \mathrm{t}_0 \tag{6a}$$

5.2.2 Linearisation of the equation

The four equations under 6a produce a non-linear set of equations. In order to solve the set, the root function is first linearised according to the Taylor model, the first part only being used (Figure 22).

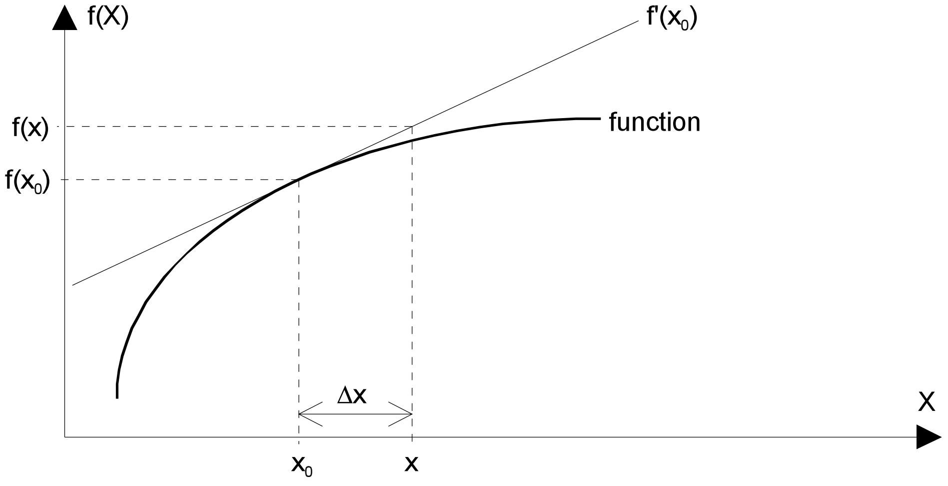


Figure 22: Conversion of the Taylor series

Generally (with $\Delta x = x - x_0$): $$f(x) = f(x_0) + \frac{f'}{1!}(x_0) \cdot \Delta x + \frac{f''}{2!}(x_0)^2 \cdot \Delta x + \frac{f'''}{3!}(x_0)^3 \cdot \Delta x + \ldots$$

Simplified (1st part only): $$f(x) = f(x_0) + f'(x_0) \cdot \Delta x \qquad (7a)$$

In order to linearise the four equations (6a), an arbitrarily estimated value x_0 must therefore be incorporated in the vicinity of x.

For the GPS system, this means that instead of calculating X_{Anw} , Y_{Anw} and Z_{Anw} directly, an estimated position X_{Ges} , Y_{Ges} and Z_{Ges} is initially used (Figure 23).

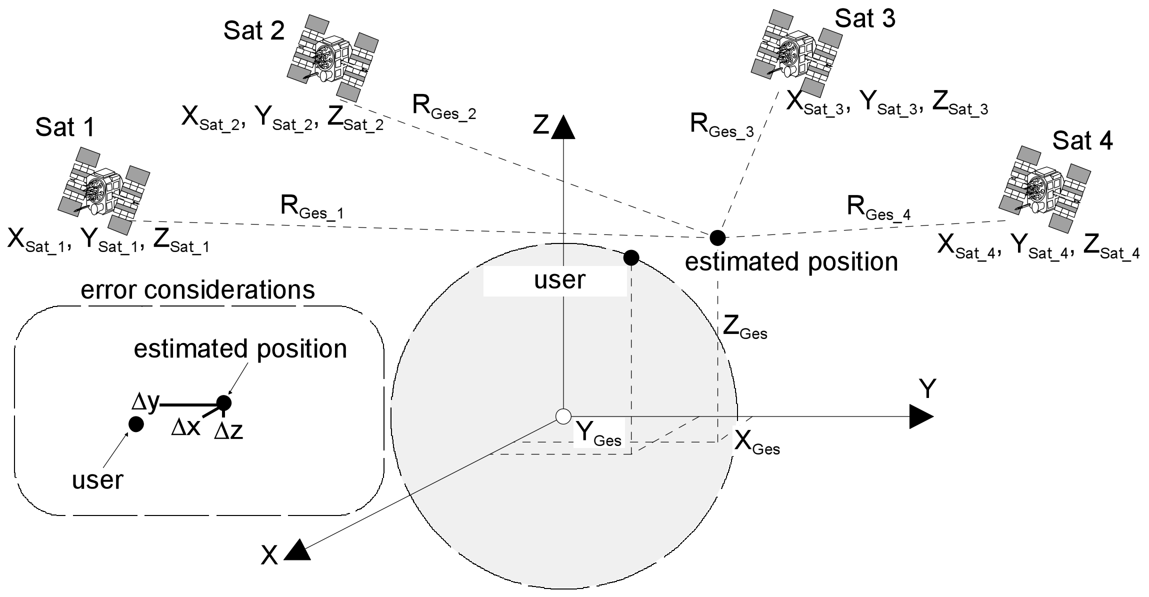


Figure 23: Estimating a position

The estimated position includes an error produced by the unknown variables Δx, Δy and Δz.

$$\begin{aligned} X_{Anw} &= X_{Ges} + \Delta x \\ Y_{Anw} &= Y_{Ges} + \Delta y \\ Z_{Anw} &= Z_{Ges} + \Delta z \end{aligned} \qquad (8a)$$

The distance R_{Ges} from the four satellites to the estimated position can be calculated in a similar way to equation (4a):

$$R_{Ges\_i} = \sqrt{\left(X_{Sat\_i} - X_{Ges}\right)^2 + \left(Y_{Sat\_i} - Y_{Ges}\right)^2 + \left(Z_{Sat\_i} - Z_{Ges}\right)^2} \qquad (9a)$$

Equation (9a) combined with equations (6a) and (7a) produces:

$$PSR_i = R_{Ges\_i} + \frac{\partial\left(R_{Ges\_i}\right)}{\partial x} \cdot \Delta x + \frac{\partial\left(R_{Ges\_i}\right)}{\partial y} \cdot \Delta y + \frac{\partial\left(R_{Ges\_i}\right)}{\partial z} \cdot \Delta z + c \cdot \Delta t_0 \qquad (10a)$$

After carrying out partial differentiation, this gives the following:

$$PSR_i = R_{Ges\_i} + \frac{X_{Ges} - X_{Sat\_i}}{R_{Ges\_i}} \cdot \Delta x + \frac{Y_{Ges} - Y_{Sat\_i}}{R_{Ges\_i}} \cdot \Delta y + \frac{Z_{Ges} - Z_{Sat\_i}}{R_{Ges\_i}} \cdot \Delta z + c \cdot \Delta t_0 \qquad (11a)$$

5.2.3 Solving the equation

After transposing the four equations (11a) (for i = 1 ... 4) the four variables (Δx, Δy, Δz and Δt_0) can now be solved according to the rules of linear algebra:

$$\begin{bmatrix} PSR_1 - R_{Ges\_1} \\ PSR_2 - R_{Ges\_2} \\ PSR_3 - R_{Ges\_3} \\ PSR_4 - R_{Ges\_4} \end{bmatrix} = \begin{bmatrix} \frac{X_{Ges} - X_{Sat\_1}}{R_{Ges\_1}} & \frac{Y_{Ges} - Y_{Sat\_1}}{R_{Ges\_1}} & \frac{Z_{Ges} - Z_{Sat\_1}}{R_{Ges\_1}} & c \\ \frac{X_{Ges} - X_{Sat\_2}}{R_{Ges\_2}} & \frac{Y_{Ges} - Y_{Sat\_2}}{R_{Ges\_2}} & \frac{Z_{Ges} - Z_{Sat\_2}}{R_{Ges\_2}} & c \\ \frac{X_{Ges} - X_{Sat\_3}}{R_{Ges\_3}} & \frac{Y_{Ges} - Y_{Sat\_3}}{R_{Ges\_3}} & \frac{Z_{Ges} - Z_{Sat\_3}}{R_{Ges\_3}} & c \\ \frac{X_{Ges} - X_{Sat\_4}}{R_{Ges\_4}} & \frac{Y_{Ges} - Y_{Sat\_4}}{R_{Ges\_4}} & \frac{Z_{Ges} - Z_{Sat\_4}}{R_{Ges\_4}} & c \end{bmatrix} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t_0 \end{bmatrix} \qquad (12a)$$

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t_0 \end{bmatrix} = \begin{bmatrix} \frac{X_{Ges} - X_{Sat\_1}}{R_{Ges\_1}} & \frac{Y_{Ges} - Y_{Sat\_1}}{R_{Ges\_1}} & \frac{Z_{Ges} - Z_{Sat\_1}}{R_{Ges\_1}} & c \\ \frac{X_{Ges} - X_{Sat\_2}}{R_{Ges\_2}} & \frac{Y_{Ges} - Y_{Sat\_2}}{R_{Ges\_2}} & \frac{Z_{Ges} - Z_{Sat\_2}}{R_{Ges\_2}} & c \\ \frac{X_{Ges} - X_{Sat\_3}}{R_{Ges\_3}} & \frac{Y_{Ges} - Y_{Sat\_3}}{R_{Ges\_3}} & \frac{Z_{Ges} - Z_{Sat\_3}}{R_{Ges\_3}} & c \\ \frac{X_{Ges} - X_{Sat\_4}}{R_{Ges\_4}} & \frac{Y_{Ges} - Y_{Sat\_4}}{R_{Ges\_4}} & \frac{Z_{Ges} - Z_{Sat\_4}}{R_{Ges\_4}} & c \end{bmatrix}^{-1} \cdot \begin{bmatrix} PSR_1 - R_{Ges\_1} \\ PSR_2 - R_{Ges\_2} \\ PSR_3 - R_{Ges\_3} \\ PSR_4 - R_{Ges\_4} \end{bmatrix} \qquad (13a)$$

The solution of Δx, Δy and Δz is used to recalculate the estimated position X_{Ges} , Y_{Ges} and Z_{Ges} in accordance with equation (8a).

$X_{Ges\_Neu} = X_{Ges\_Alt} + \Delta x$

$Y_{Ges\_Neu} = Y_{Ges\_Alt} + \Delta y$

$Z_{Ges\_Neu} = Z_{Ges\_Alt} + \Delta z$ (14a)

The estimated values X_{Ges_Neu} , Y_{Ges_Neu} and Z_{Ges_Neu} can now be entered into the set of equations (13a) using the normal iterative process, until error components Δx, Δy and Δz are smaller than the desired error (e.g. 0.1 m). Depending on the initial estimation, three to five iterative calculations are generally required to produce an error component of less than 1 cm.

5.2.4 Summary

In order to determine a position, the user (or his receiver software) will either use the last measurement value, or estimate a new position and calculate error components (Δx, Δy and Δz) down to zero by repeated iteration. This then gives:

$X_{Anw} = X_{Ges\_Neu}$
$Y_{Anw} = Y_{Ges\_Neu}$
$Z_{Anw} = Z_{Ges\_Neu}$ (15a)

The calculated value of Δt_0 corresponds to receiver time error and can be used to adjust the receiver clock.

5.2.5 Error consideration and satellite signal

5.2.5.1 Error consideration

Error components in calculations have so far not been taken into account. In the case of the GPS system, several causes may contribute to the overall error:

- Satellite clocks: although each satellite has four atomic clocks on board, a time error of just 10 ns creates an error in the order of 3 m.
- Satellite orbits: The position of a satellite is generally known only to within approx. 1 to 5 m.
- Speed of light: the signals from the satellite to the user travel at the speed of light. This slows down when traversing the ionosphere and troposphere and can therefore no longer be taken as a constant.
- Measuring signal transit time: The user can only determine the point in time at which an incoming satellite signal is received to within a period of approx. 10-20 ns, which corresponds to a positional error of 3-6 m. The error component is increased further still as a result of terrestrial reflection (multipath).
- Satellite geometry: The ability to determine a position deteriorates if the four satellites used to take measurements are close together. The effect of satellite geometry on accuracy of measurement (see 5.2.5.2) is referred to as GDOP (Geometric Dilution Of Precision).

The errors are caused by various factors that are detailed in Table 4, which includes information on horizontal errors. 1 sigma (68.3%) and 2 sigma (95.5%) are also given. Accuracy is, for the most part, better than specified, the values applying to an average satellite constellation (DOP value) [ix].

Cause of error	**Error**
Effects of the ionosphere	4 m
Satellite clocks	2.1 m
Receiver measurements	0.5 m
Ephemeris data	2.1
Effects of the troposphere	0.7
Multipath	1.4 m
Total RMS value (unfiltered)	5.3 m
Total RMS value (filtered)	5.1
Vertical error (1 sigma (68.3%) VDOP=2.5)	12.8m
Vertical error (2 sigma (95.5.3%) VDOP=2.5)	**25.6m**
Horizontal error (1 sigma (68.3%) HDOP=2.0)	10.2m
Horizontal error (2 sigma (95.5%) HDOP=2.0)	**20.4m**

Table 4: Cause of errors

Measurements undertaken by the US Federal Aviation Administration over a long period of time indicate that in the case of 95% of all measurements, horizontal error is under 7.4 m and vertical error is under 9.0 m. In all cases, measurements were conducted over a period of 24 hours [iv].

In many instances, the number of error sources can be eliminated or reduced (typically to 1...2 m, 2 sigma) by taking appropriate measures (Differential GPS, DGPS).

5.2.5.2 DOP (dilution of precision)

The accuracy with which a position can be determined using GPS in navigation mode depends, on the one hand, on the accuracy of the individual pseudo-range measurements, and on the other, on the geometrical configuration of the satellites used. This is expressed in a scalar quantity, which in navigation literature is termed DOP (Dilution of Precision).

There are several DOP designations in current use:

- GDOP: Geometrical DOP (position in 3-D space, incl. time deviation in the solution)
- PDOP: Positional DOP (position in 3-D space)
- HDOP: Horizontal DOP (position on a plane)
- VDOP: Vertical DOP (height only)

The accuracy of any measurement is proportionately dependent on the DOP value. This means that if the DOP value doubles, the error in determining a position increases by a factor of two.

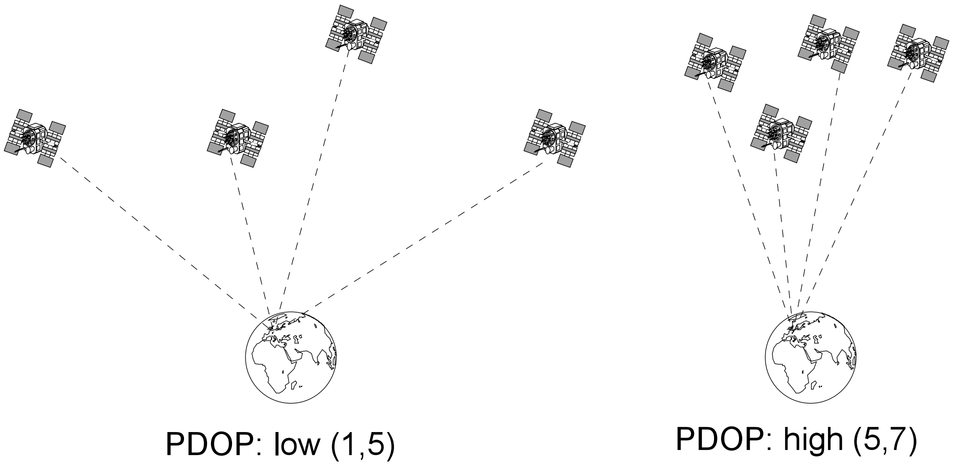


Figure 24: Satellite geometry and PDOP

PDOP can be interpreted as a reciprocal value of the volume of a tetrahedron, formed by the positions of the satellites and user, as shown in Figure 24. The best geometrical situation occurs when the volume is at a maximum and PDOP at a minimum.

PDOP played an important part in the planning of measurement projects during the early years of GPS, as the limited deployment of satellites frequently produced phases when satellite constellations were geometrically very unfavourable. Satellite deployment today is so good that PDOP and GDOP values rarely exceed 3 (Figure 1).

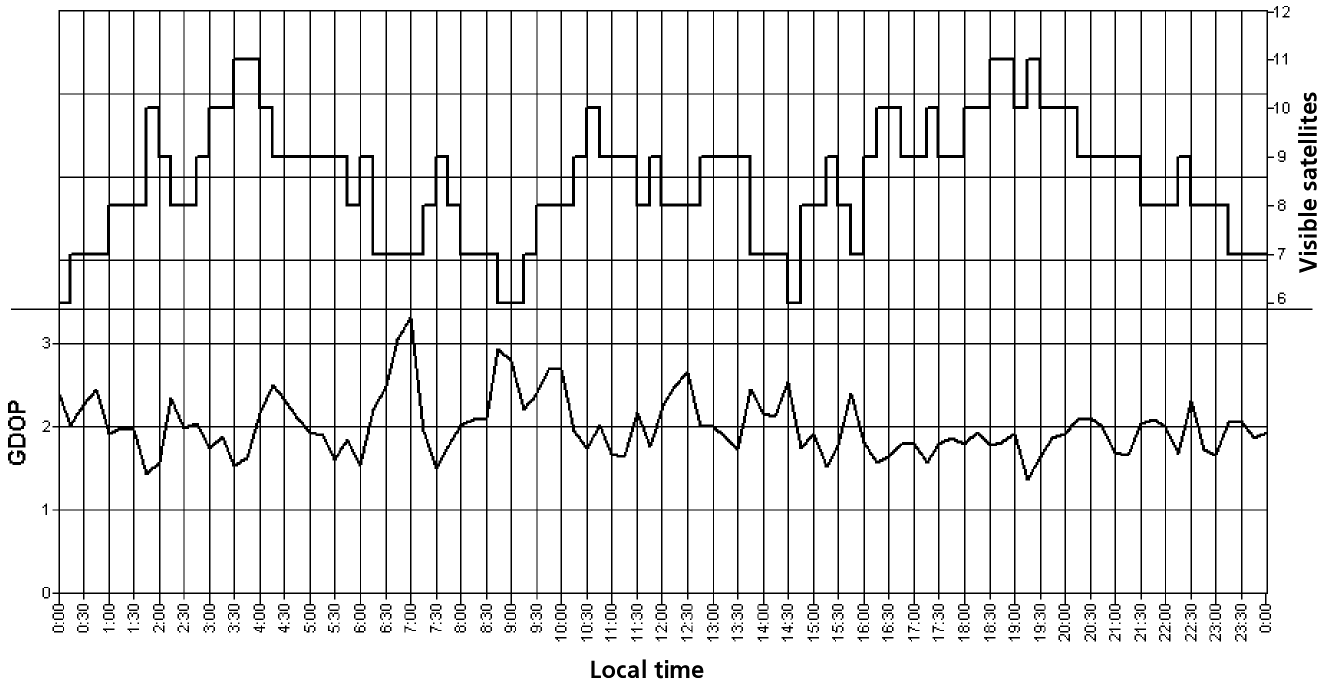


Figure 25: GDOP values and the number of satellites expressed as a time function

It is therefore unnecessary to plan measurements based on PDOP values, or to evaluate the degree of accuracy attainable as a result, particularly as different PDOP values can arise over the course of a few minutes. In the case of kinematic applications and rapid recording processes, unfavourable geometrical situations that are short lived in nature can occur in isolated cases. The relevant PDOP values should therefore be included as evaluation criteria when assessing critical results. PDOP values can be shown with all planning and evaluation programmes supplied by leading equipment manufacturers (Figure 26).

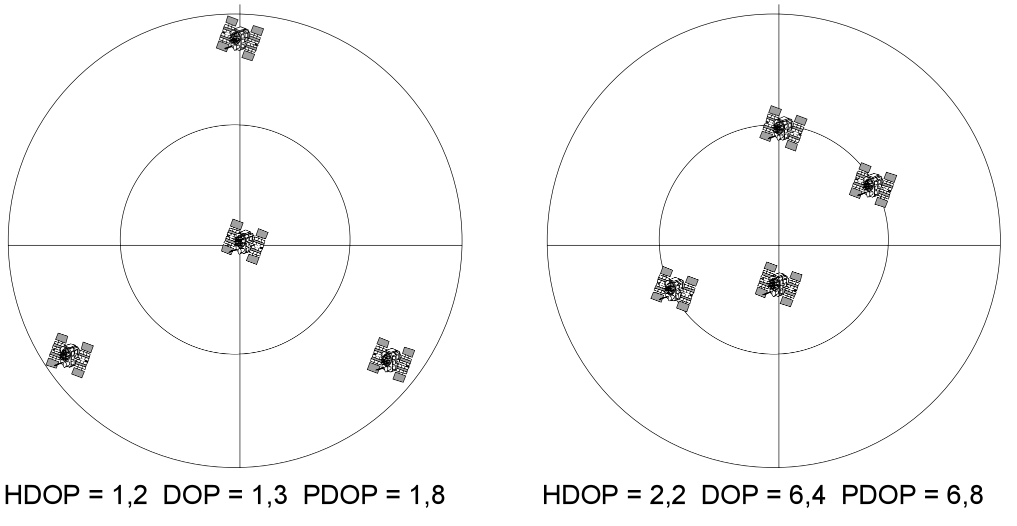


Figure 26: Effect of satellite constellations on the DOP value

6 CO-ORDINATE SYSTEMS

If you would like to . . .

- know what a geoid is
- understand why the Earth is depicted primarily as an ellipsoid
- understand why over 200 different map reference systems are used worldwide
- know what WGS-84 means
- understand how it is possible to convert one datum into another
- know what Cartesian and ellipsoidal co-ordinates are
- understand how maps of countries are made
- know how country co-ordinates are calculated from the WGS-84 co-ordinates

then ***this chapter*** *is for you!*

6.1 Introduction

A significant problem when using the GPS system is that there are very many different co-ordinate systems worldwide. As a result, the position measured and calculated by the GPS system does not always coincide with one's supposed position.

In order to understand how the GPS system functions, it is necessary to take a look at the basics of the science that deals with the surveying and mapping of the Earth's surface, geodesy. Without this basic knowledge, it is difficult to understand why with a good portable GPS receiver the right combination has to be selected from more than 100 different map reference systems (datum) and approx. 10 different grids. If an incorrect choice is made, a position can be out by several hundred meters.

6.2 Geoids

We have known that the Earth is round since Columbus. But how round is it really? Describing the shape of the blue planet exactly has always been an imprecise science. Several different methods have been attempted over the course of the centuries to describe as exactly as possible the true shape of the Earth. A geoid represents an approximation of this shape.

In an ideal situation, the smoothed, average sea surface forms part of a level surface, which in a geometrical sense is the "surface" of the Earth. By analogy with the Greek word for Earth, this surface is described as a geoid (Figure 27).

A geoid can only be defined as a mathematical figure with a limited degree of accuracy and not without a few arbitrary assumptions. This is because the distribution of the mass of the Earth is uneven and, as a result, the level surface of the oceans and seas do not lie on the surface of a geometrically definable shape; instead approximations have to be used.

Differing from the actual shape of the Earth, a geoid is a theoretical body whose surface intersects the gravitational field lines everywhere at right angles.

A geoid is often used as a reference surface for measuring height. The reference point in Switzerland for measuring height is the "Repère Pierre du Niton (RPN, 373.600 m) in the Geneva harbour basin. This height originates from point to point measurements with the port of Marseilles (mean height above sea level 0.00m).

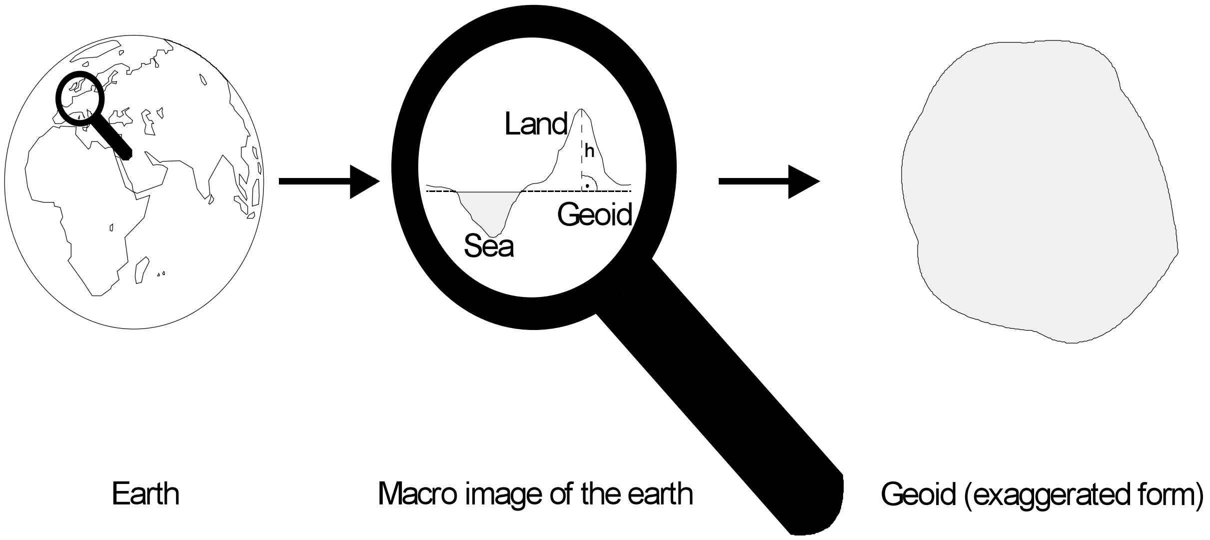


Figure 27: A geoid is an approximation of the Earth's surface

6.3 Ellipsoid and datum

6.3.1 Spheroid

A geoid, however, is a difficult shape to manipulate when conducting calculations. A simpler, more definable shape is therefore needed when carrying out daily surveying operations. Such a substitute surface is known as a spheroid. If the surface of an ellipse is rotated about its symmetrical north-south pole axis, a spheroid is obtained as a result. (Figure 28).

A spheroid is defined by two parameters:

- Semi major axis a (on the equatorial plane)
- Semi minor axis b (on the north-south pole axis)

The amount by which the shape deviates from the ideal sphere is referred to as flattening (f).

$$f = \frac{a-b}{a} \tag{16a}$$

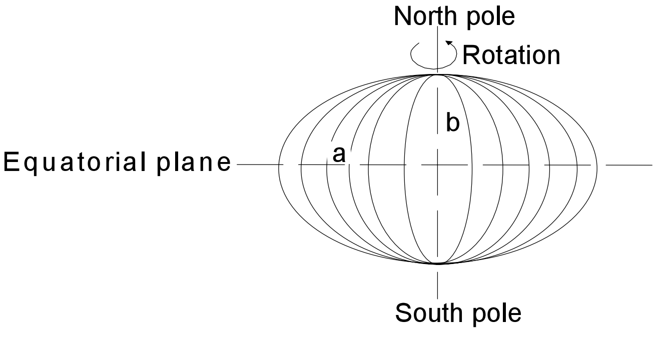


Figure 28: Producing a spheroid

6.3.2 Customised local reference ellipsoids and datum

6.3.2.1 Local reference ellipsoids

When dealing with a spheroid, care must be taken to ensure that the natural perpendicular does not intersect vertically at a point with the ellipsoid, but the geoid. Normal ellipsoidal and natural perpendiculars do not therefore coincide, they are distinguished by "vertical deflection" (Figure 30), i.e. points on the Earth's surface are incorrectly projected. In order to keep this deviation to a minimum, each country has developed its own customised non-geocentric spheroid as a reference surface for carrying out surveying operations (Figure 29). The semiaxes a and b and the mid-point are selected in such a way that the geoid and ellipsoid match national territories as accurately as possible.

6.3.2.2 Datum, map reference systems

National or international map reference systems based on certain types of ellipsoids are called datums. Depending on the map used when navigating with GPS receivers, care should be taken to ensure that the relevant map reference system has been entered into the receiver.

Some examples of these map reference systems from a selection of over 120 are CH-1903 for Switzerland, WGS-84 as the global standard, and NAD83 for North America.

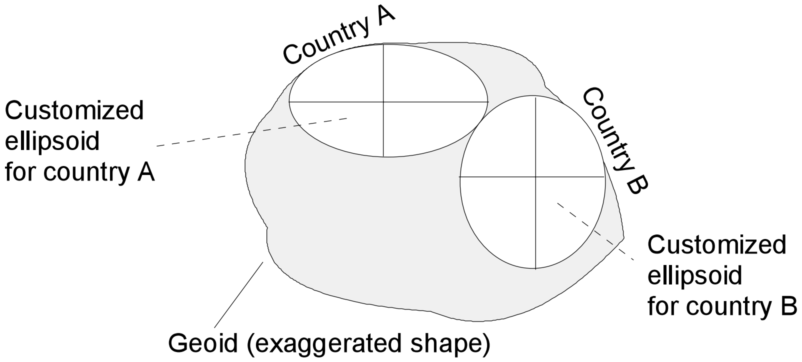


Figure 29: Customised local reference ellipsoid

A spheroid is well suited for describing the positional co-ordinates of a point in degrees of longitude and latitude. Information on height is either based on the geoid or the reference ellipsoid. The difference between the measured orthometric height H, i.e. based on the geoid, and the ellipsoidal height h, based on the reference ellipsoid, is known as geoid ondulation N (Figure 30)

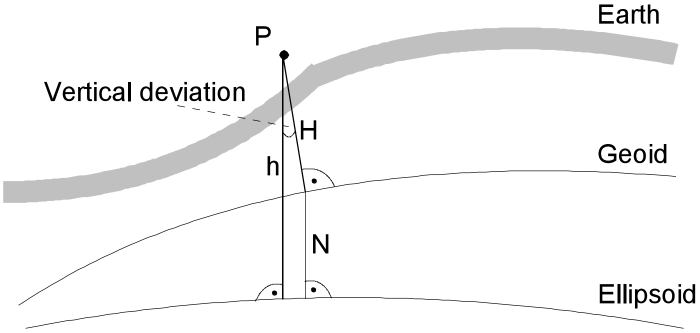


Figure 30: Difference between geoid and ellipsoid

6.3.3 National reference systems

Different reference systems are used throughout Europe, and each reference system employed for technical applications during surveying has its own name. The non-geocentric ellipsoids that form the basis of these are summarised in the following table (Table 5). If the same ellipsoids are used, they are distinguished from country to country in respect of their local references.

Country	**Name**	**Reference ellipsoid**	**Local reference**	**Semi major axis a (m)**	**Flattening (1: ...)**
Germany	Potsdam	Bessel 1841	Rauenberg	6377397.155	299.1528128
France	NTF	Clarke 1880	Pantheon, Paris	6378249.145	293.465
Italy	SI 1940	Hayford 1928	Monte Mario, Rome	6378388.0	297.0
Netherlands	RD/NAP	Bessel 1841	Amersfoort	6377397.155	299.1528128
Austria	MGI	Bessel 1841	Hermannskogel	6377397.155	299.1528128
Switzerland	CH1903	Bessel 1841	Old Observatory Bern	6377397.155	299.1528128
International	Hayford	Hayford	Country independent	6378388.000	297.000

Table 5: National reference systems

6.3.4 Worldwide reference ellipsoid WGS-84

The details displayed and calculations made by a GPS receiver primarily involve the WGS-84 (World Geodetic System 1984) reference system. The WGS-84 co-ordinate system is geocentrically positioned with respect to the centre of the Earth. Such a system is called ECEF (Earth Centered, Earth Fixed). The WGS-84 co-ordinate system is a three-dimensional, right-handed, Cartesian co-ordinate system with its original co-ordinate point at the centre of mass (= geocentric) of an ellipsoid, which approximates the total mass of the Earth.

The positive X-axis of the ellispoid (Figure 31) lies on the equatorial plane (that imaginary surface which is encompassed by the equator) and extends from the centre of mass through the point at which the equator and the Greenwich meridian intersect (the 0 meridian). The Y-axis also lies on the equatorial plane and is offset 90° to the east of the X-axis. The Z-axis lies perpendicular to the X and Y-axis and extends through the geographical north pole.

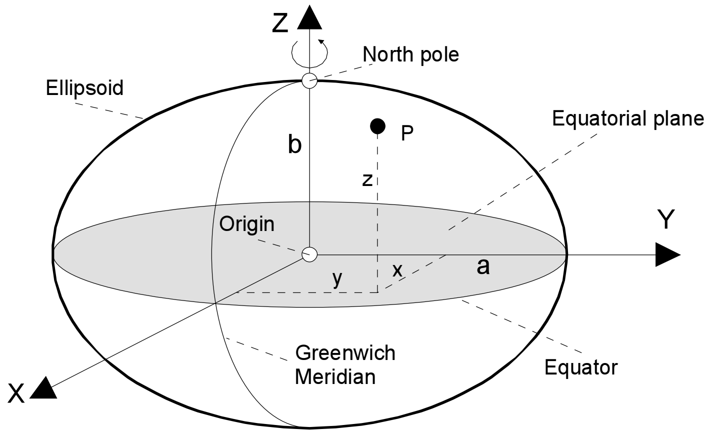


Figure 31: Illustration of the Cartesian co-ordinates

Parameters of the WGS-84 reference ellipsoid		
Semi major axis a (m)	Semi minor axis b (m)	Flattening (1: ....)
6,378,137.00	6,356,'752.31	298,257223563

Table 6: The WGS-84 ellipsoid

Ellipsoidal co-ordinates (φ, λ, h), rather than Cartesian co-ordinates (X, Y, Z) are generally used for further processing (Figure 32). φ corresponds to latitude, λ to longitude and h to the ellipsoidal height, i.e. the length of the vertical P line to the ellipsoid.

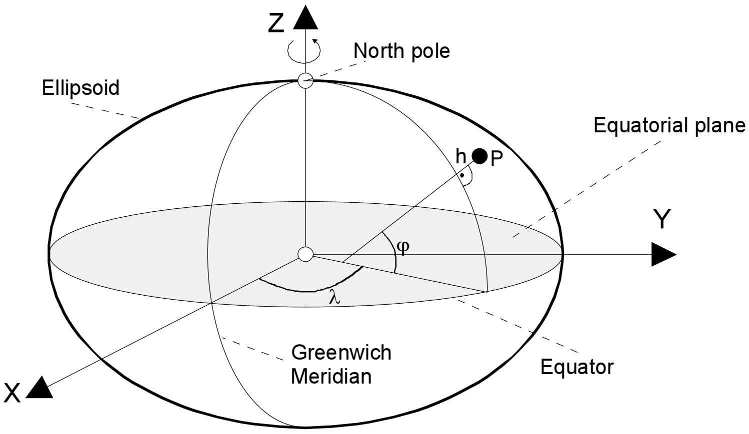


Figure 32: Illustration of the ellipsoidal co-ordinates

6.3.5 Transformation from local to worldwide reference ellipsoid

6.3.5.1 Geodetic datum

As a rule, reference systems are generally local rather than geocentric ellipsoids. The relationship between a local (e.g. CH-1903) and a global, geocentric system (e.g. WGS-84) is referred to as the geodetic datum. In the event that the axes of the local and global ellipsoid are parallel, or can be regarded as being parallel for applications within a local area, all that is required for datum transition are three shift parameters, known as the datum shift constants ΔX, ΔY, ΔZ.

A further three angles of rotation φx, φy, φz and a scaling factor m (Figure 33) may have to be added so that the complete transformation formula contains 7 parameters. The geodetic datum specifies the location of a local three-dimensional Cartesian co-ordinate system with regard to the global system.

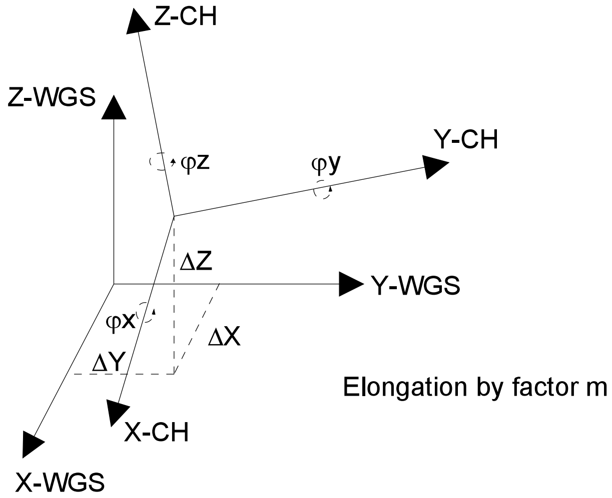


Figure 33: Geodetic datum

The following table (Table 7) shows examples of the various datum parameters. Additional values can be found under [x].

Country	Name	ΔX (m)	ΔY (m)	ΔZ (m)	φx (´´)	φx (´´)	φx (´´)	m (ppm)
Germany	Potsdam	586	87	409	-0.52	-0.15	2.82	9
France	NTF	-168	-60	320	0	0	0	1
Italy	SI 1940	-225	-65	9	-	-	-	-
Netherlands	RD/NAP	565.04	49.91	465.84	0.4094	-0.3597	1.8685	4.0772
Austria	MGI	-577.326	-577.326	-463.919	5.1366	1.4742	5.2970	-2.4232
Switzerland	CH1903	660.077	13.551	369.344	0.8065	0.5789	0.9542	5.66

Table 7: Datum parameters

6.3.5.2 Datum conversion

Converting a datum means by definition converting one three-dimensional Cartesian co-ordinate system (e.g. WGS-84) into another (e.g. CH-1903) by means of three-dimensional shift, rotation and extension. The geodetic datum must be known, in order to effect the conversion. Comprehensive conversion formulae can be found in specialist literature [xi], or conversion can be carried out direct via the Internet [xii]. Once conversion has taken place, Cartesian co-ordinates can be transformed into ellipsoidal co-ordinates.

6.3.6 Converting co-ordinate systems

6.3.6.1 Converting Cartesian to ellipsoidal co-ordinates

Cartesian and ellipsoidal co-ordinates can be converted from one representation to the other. Conversion is, however, dependent on the quandrant in which one is located. The conversion for central Europe is given here as an example. This means that the x, y and z values are positive. [xiii]

$$\varphi=\tan^{-1}\left[\frac{z+\left[\left(\frac{a^2-b^2}{b^2}\right)\cdot b\cdot\left[\sin\left[\tan^{-1}\left[\frac{z\cdot a}{\left(\sqrt{x^2+y^2}\right)\cdot b}\right]\right]\right]^3\right]}{\left(\sqrt{x^2+y^2}\right)-\left(\frac{a^2-b^2}{a^2}\right)\cdot a\cdot\left[\cos\left[\tan^{-1}\left[\frac{z\cdot a}{\left(\sqrt{x^2+y^2}\right)\cdot b}\right]\right]\right]^3}\right] \tag{17a}$$

$$\lambda=\tan^{-1}\left(\frac{y}{x}\right) \tag{18a}$$

$$h=\frac{\sqrt{x^2+y^2}}{\cos(\varphi)}-\frac{a}{\sqrt{1-\left(\frac{a^2-b^2}{a^2}\right)\cdot[\sin(\varphi)]^2}} \tag{19a}$$

6.3.6.2 Converting ellipsoidal to Cartesian co-ordinates

Ellipsoidal co-ordinates can be converted into Cartesian co-ordinates.

$$x=\left[\frac{a}{\sqrt{1-\left(\frac{a^2-b^2}{a^2}\right)\cdot[\sin(\varphi)]^2}}+h\right]\cdot\cos(\varphi)\cdot\cos(\lambda) \tag{20a}$$

$$y=\left[\frac{a}{\sqrt{1-\left(\frac{a^2-b^2}{a^2}\right)\cdot[\sin(\varphi)]^2}}+h\right]\cdot\cos(\varphi)\cdot\sin(\lambda) \tag{21a}$$

$$z=\left[\frac{a}{\sqrt{1-\left(\frac{a^2-b^2}{a^2}\right)\cdot[\sin(\varphi)]^2}}\cdot\left[1-\left(\frac{a^2-b^2}{a^2}\right)\right]+h\right]\cdot\sin(\varphi) \tag{22a}$$

6.4 Planar land survey co-ordinates, projection

Normally, when carrying out ordnance surveys, the position of a point P on the Earth's surface is described by the ellipsoidal co-ordinates of latitude φ and longitude λ (based on the reference ellipsoid) as well as height (based on an ellipsoid or geoid) (Figure 32).

As geodetic calculations (e.g. the distance between two buildings) on an ellipsoid are numerically inconvenient, ellipsoidal projections onto a mathematical plane are used in technical surveying operations. This produces smooth, right-angled X and Y land survey co-ordinates. Most maps contain a grid enabling a point to be easily located anywhere in a terrain. In ordnance surveying, planar co-ordinates are projections of reference ellipsoid co-ordinates onto a mathematical plane. Projecting an ellipsoid onto a plane is not possible without distorting it, but it is possible to opt for a method of projection that keeps distortion to a minimum. Standard types of projection include cylindrical or Mercator projection, Gauss-Krüger projection, UTM projection and Lambert conic projection. If positional data is used in conjunction with maps, special attention must be paid to the type of reference system and projection used in producing the maps.

6.4.1 Projection system for Germany and Austria

At present, Germany and Austria primarily use Gauss-Krüger projection, but both countries are either planning to extend this to include UTM projection (Universal Transversal Mercator Projection) or have already made the switch.

6.4.1.1 Gauss-Krüger projection (Transverse Mercator Projection)

Gauss-Krüger projection is a tangential, conformal, transverse Mercator projection. An elliptical cylinder is positioned around the spheroid, the cylinder casing coming into contact with the ellipsoid along its entire Greenwich Meridian and in the vicinity of the poles. In order to keep longitudinal and surface distortion to a minimum, three zones 3° in width are taken from the Bessel ellipsoid. The width of the zone is positioned around the prime meridian. The cylinder is situated at a transverse angle to the ellipsoid, i.e. rotated by 90° (Figure 34).

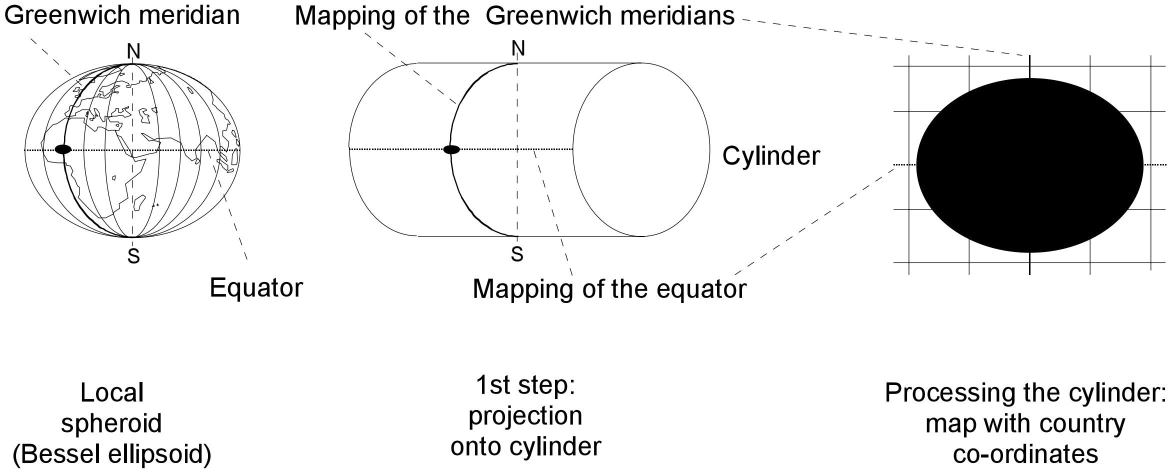


Figure 34: Gauss-Krüger projection

In order that the co-ordinates are not negative, particularly those to the west of the prime meridian, easting is applied as a corrective process (e.g. 500 km).

6.4.1.2 UTM projection

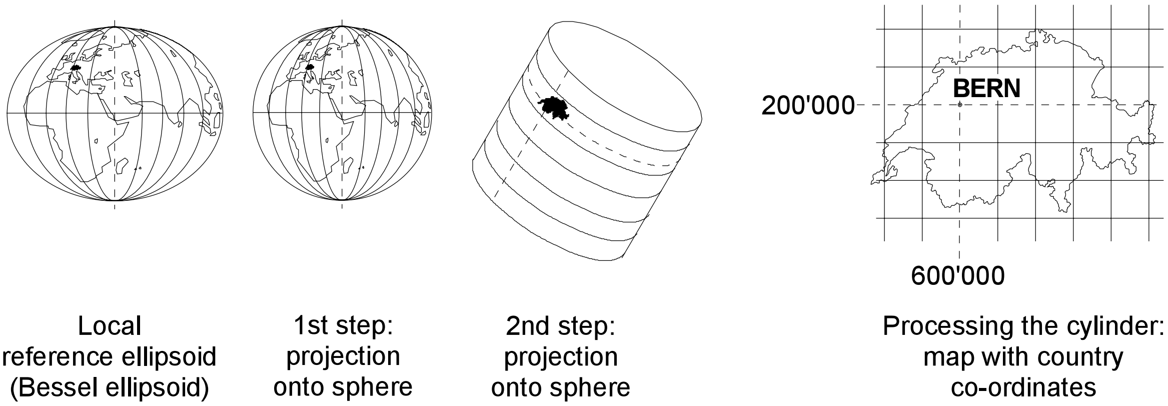
UTM projection (Universal Transverse Mercator Projection) is virtually identical to Gauss-Krüger projection. The only difference is that the Greenwich meridian is not accurate in terms of longitude, but projected at a constant scale of 0.9996, and the zones are 6° in width.

6.4.2 Swiss projection system (conformal double projection)

The conformal projection of a Bessel ellipsoid onto a plane takes place in two stages. The ellipsoid is initially projected onto a sphere, and then the sphere is projected onto a plane via a cylinder set at an oblique angle. This process is known as double projection (Figure 35). A main point on the ellipsoid (Old Observatory in Bern) is positioned on the plane when mapping the original co-ordinate system (with offset: Y_{Ost} = 600,000 m and X_{Nord} = 200,000 m).

Two different sets of co-ordinates are marked on the map of Switzerland (e.g. scale 1:25000):

- Land co-ordinates (X and Y in kilometers) projected onto the plane with an accompanying grid and
- the geographical co-ordinates (longitude and latitude in degrees and seconds) based on the Bessel ellipsoid



Local reference ellipsoid (Bessel ellipsoid)

1st step: projection onto sphere

2nd step: projection onto sphere

Processing the cylinder: map with country co-ordinates

Figure 35: The principle of double projection

The signal transit time from 4 satellites must be known by the time the positional co-ordinates are issued. Only then, after considerable calculation and conversion, is the position issued in Swiss land survey co-ordinates).

The signal transit time from 4 satellites must be known by the time the positional co-ordinates are issued. Only then, after considerable calculation and conversion, is the position issued in Swiss land survey co-ordinates (Figure 36).

Figure 36: From satellite to position

6.4.3 Worldwide co-ordinate conversion

There are several possibilities on the Internet for converting one co-ordinate system into another. [xiv].

6.4.3.1 Converting WGS-84 co-ordinates into CH-1903 co-ordinates, as an example

(Taken from "Bezugssysteme in der Praxis" (practical reference systems) by Urs Marti and Dieter Egger, Federal Office for National Topography)

Note that the accuracy is in the order of **1 meter**!

1. Converting longitude and latitude:

Longitude and latitude in WGS-84 data have to be converted into sexagesimal seconds [″].

Example:

1. When converted, latitude 46° 2′ 38.87″ (WGS-84) becomes 165758.87″. This quantity is designated as B: B = 165758.87″.
2. When converted, longitude 8° 43′ 49.79″ (WGS-84) becomes 31429.79″. This quantity is designated as L: L = 31429.79″.

2. Calculating auxiliary quantities:

$$\Phi = \frac{B - 169028.66''}{10000} \qquad \Lambda = \frac{L - 26782.5''}{10000}$$

Example:

$$\Phi = -\,0.326979$$
$$\Lambda = 0.464729$$

3. Calculating the abscissa (W---E): y

$$y[m] = 600072.37 + (211455.93 * \Lambda) - (10938.51 * \Lambda * \Phi) - (0.36 * \Lambda * \Phi^2) - (44.54 * \Lambda^3)$$

Example: y = 700000.0m

4. Calculating the ordinate (S---N): x

$$x[m] = 200147.07 + (308807.95 * \Phi) + (3745.25 * \Lambda^2) + (76.63 * \Phi^2) - (194.56 * \Lambda^2 * \Phi) + (119.79 * \Phi^3)$$

Example: x = 100000.0m

5. Calculating the height H:

$$H[m] = (Height_{WGS-84} - 49.55) + (2.73 * \Lambda) + (6.94 * \Phi)$$

Example:

After conversion, height_{WGS-84} = 650.60m produces: H = 600m

7 DIFFERENTIAL-GPS (DGPS)

If you would like to . . .

- know what DGPS means
- know how correction values are determined and relayed
- understand how the D-signal corrects erroneous positional measurements
- know what DGPS services are available in Central Europe
- know what EGNOS and WAAS mean

*then **this chapter** is for you!*

7.1 Introduction

A horizontal accuracy of approx. 20 m is probably not sufficient for every situation. In order to determine the movement of concrete dams down to the nearest millimetre, for example, a greater degree of accuracy is required. In principle, a reference receiver is always used in addition to the user receiver. This is located at an accurately measured reference point (i.e. the co-ordinates are known). By continually comparing the user receiver with the reference receiver, many errors (even SA ones, if it is switched on) can be eliminated. This is because a difference in measurement arises, which is known as Differential GPS (DGPS). The process involves two different principles:

- DGPS based on the measurement of signal transit time (achievable accuracy approx. 1 m)
- DGPS based on the phase measurement of the carrier signal (achievable accuracy approx. 1 cm)

In the case of differential processes in use today, a general distinction is drawn between the following:

- Local area differential GPS
- Regional area differential GPS
- Wide area differential GPS

Several DGPS services are introduced in section A.1.

7.2 DGPS based on the measurement of signal transit time

In theory, the achievable level of accuracy based on the processes currently described is approx. 15-20 m. For surveying operations requiring an accuracy of approx. 1 cm and for demanding feats of navigation, accuracy has to be increased. Industry has discovered a straightforward and reliable solution to this problem: differential GPS (DGPS). The principle of DGPS is very simple. A GPS reference station is set up at a known, accurately surveyed point. The GPS reference station determines a person’s position by means of four satellites. As the exact position of the reference station is known, it is possible to calculate any deviation from the actual position measured. This deviation (differential position) also holds good for any GPS receivers within a 200 km radius of the reference station. The differential position can therefore be used to correct positions measured by other GPS receivers (Figure 37). Any deviation in position can either be relayed directly by radio, or corrections can subsequently be made after the measurements have been made. Based on this principle, accuracy to within a few millimeters can be achieved.

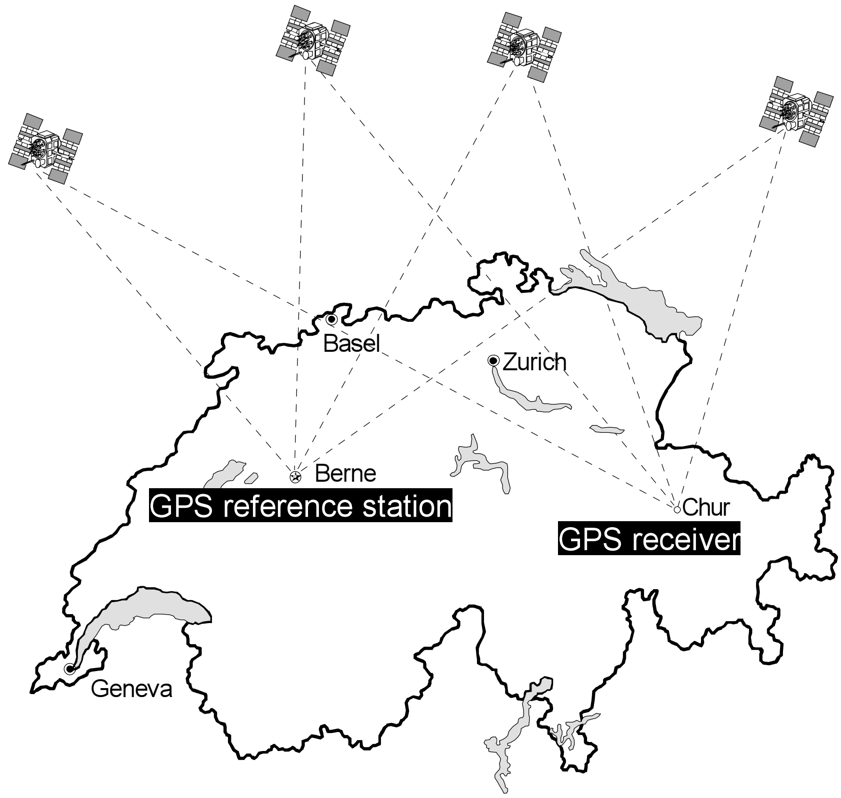


Figure 37: Principle operation of GPS with a GPS reference station

7.2.1 Detailed DGPS method of operation

The effects of the ionosphere are directly responsible for inaccurate data. In DGPS, a technology is now available that can compensate for most of the errors. Compensation takes place in three phases:

1. Determining the correction values at the reference station
2. Relaying the correction values from the reference station to the GPS user
3. Correcting the pseudo-range measured by the GPS user

7.2.1.1 Determining the correction values

A reference station whose co-ordinates are precisely known measures signal transit time to all visible GPS satellites (Figure 38) and determines the pseudo-range from this variable (actual value). Because the position of the reference station is known precisely, it is possible to calculate the true distance (target value) to each GPS satellite. The difference between the true value and the pseudo-range can be ascertained by simple subtraction and will give the correction value (difference between the actual and target value). The correction value is different for every GPS satellite and will hold good for every GPS user within a radius of a few hundred kilometers.

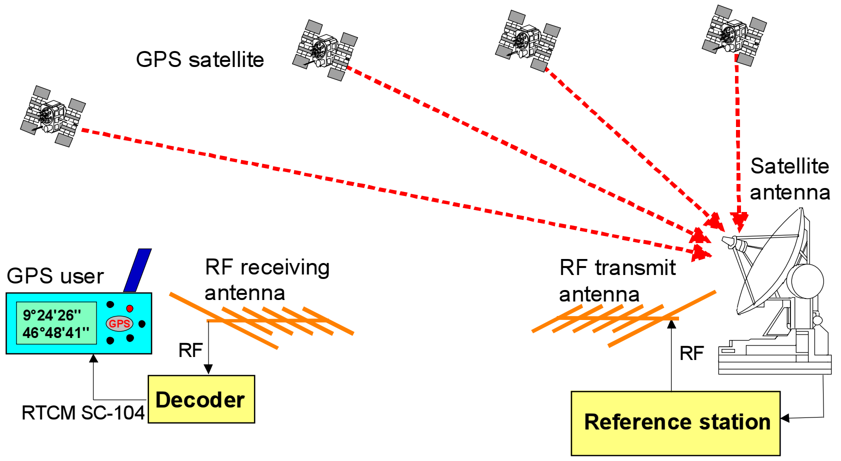


Figure 38: Determining the correction values

7.2.1.2 Relaying the correction values

As the correction values can be used within a wide area to correct measured pseudo-range, they are relayed without delay via a suitable medium (transmitter, telephone, radio, etc.) to other GPS users (Figure 39).

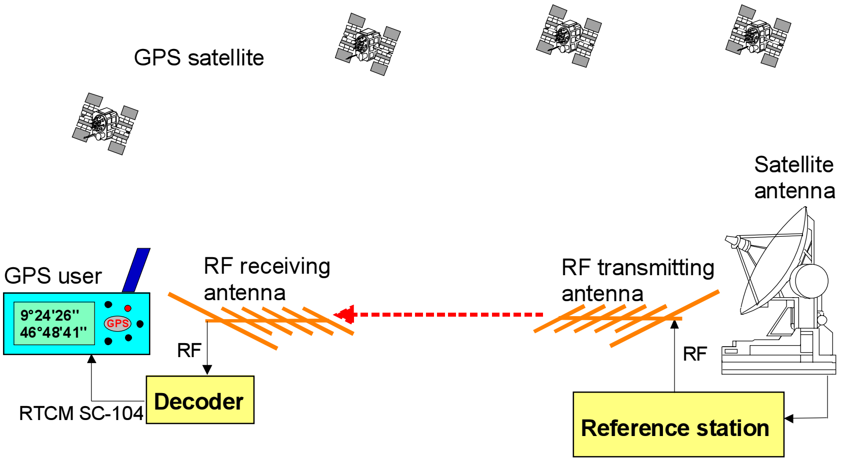


Figure 39: Relaying the corrction values

7.2.1.3 Correcting measured pseudo-range

After receiving the correction values, a GPS user can determine the true distance using the pseudo- range he has measured (Figure 40). The exact user position can now be calculated from the true distance. All causes of error can therefore be eliminated with the exception of those emanating from receiver noise and mutlipath.

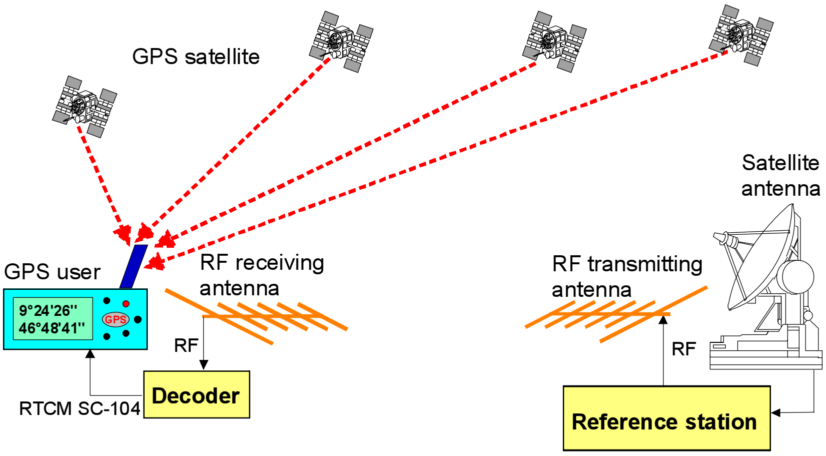


Figure 40: Correcting measured pseudo-range

7.3 DGPS based on carrier phase measurement

When measuring pseudo-range an achievable accuracy of 1 meter is still not adequate for solving problems during surveying operations. In order to be able to carry out measurements to within a few millimeters, the satellite signal carrier phase must be evaluated. The carrier wavelength λ is approx. 19 cm. The range to a satellite can be determined using the following method (Figure 41).

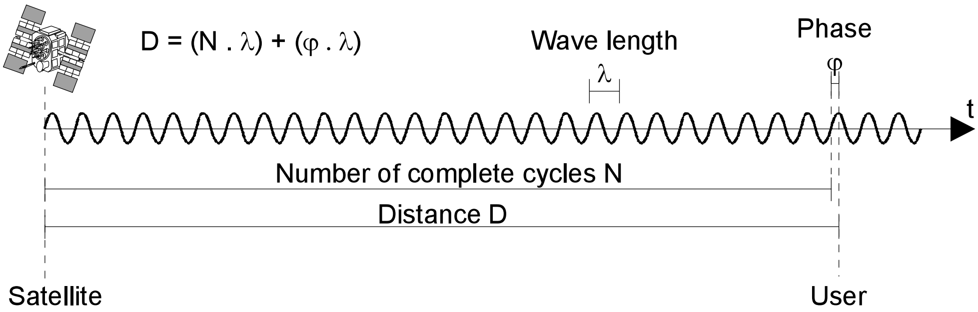


Figure 41: The principle of phase measurement

Phase measurement is an uncertain process, because N is unknown. By observing several satellites at different times and by continually comparing the user receiver with the reference receiver (during or after the measurement) a position can be determined to within a few millimeters after having solved numerous sets of equations.

8 DATA FORMATS AND HARDWARE INTERFACES

If you would like to . . .

- know what NMEA and RTCM mean
- know what a proprietary data set is
- know what data set is available in the case of all GPS receivers
- know what an active antenna is
- know whether GPS receivers have a synchronised timing pulse

*then **this chapter** is for you!*

8.1 Introduction

GPS receivers require different signals in order to function (Figure 42). These variables are broadcast after position and time have been successfully calculated and determined. To ensure that the different types of appliances are portable there are either international standards for data exchange (NMEA and RTCM), or the manufacturer provides defined (proprietary) formats and protocols.

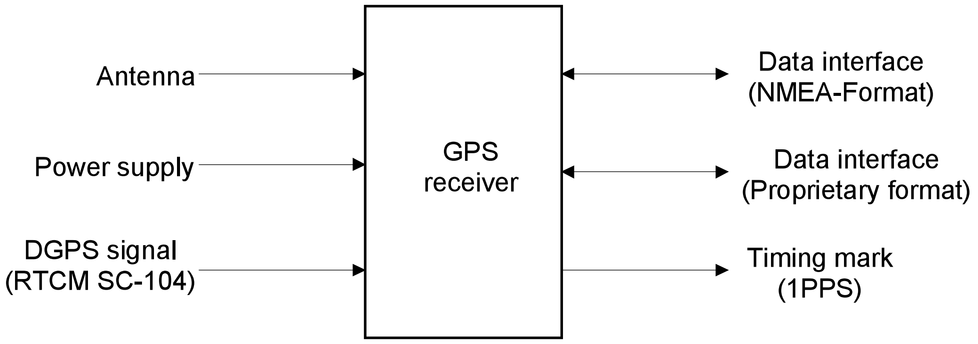


Figure 42: Block diagram of a GPS receiver with interfaces

8.2 Data interfaces

8.2.1 The NMEA-0183 data interface

In order to relay computed GPS variables such as position, velocity, course etc. to a peripheral (e.g. computer, screen, transceiver), GPS modules have a serial interface (TTL or RS-232 level). The most important elements of receiver information are broadcast via this interface in a special data format. This format is standardised by the National Marine Electronics Association (NMEA) to ensure that data exchange takes place without any problems. Nowadays, data is relayed according to the NMEA-0183 specification. NMEA has specified data sets for various applications e.g. GNSS (Global Navigation Satellite System), GPS, Loran, Omega, Transit and also for various manufacturers. The following seven data sets are widely used with GPS modules to relay GPS information [XV]:

1. GGA (GPS Fix Data, fixed data for the Global Positioning System)
2. GLL (Geographic Position – Latitude/Longitude)
3. GSA (GNSS DOP and Active Satellites, degradation of accuracy and the number of active satellites in the Global Satellite Navigation System)
4. GSV (GNSS Satellites in View, satellites in view in the Global Satellite Navigation System)
5. RMC (Recommended Minimum Specific GNSS Data)
6. VTG (Course over Ground and Ground Speed, horizontal course and horizontal velocity)
7. ZDA (Time & Date)

8.2.1.1 Structure of the NMEA protocol

In the case of NMEA, the rate at which data is transmitted is 4800 Baud using printable 8-bit ASCII characters. Transmission begins with a start bit (logical zero), followed by eight data bits and a stop bit (logical one) added at the end. No parity bits are used.

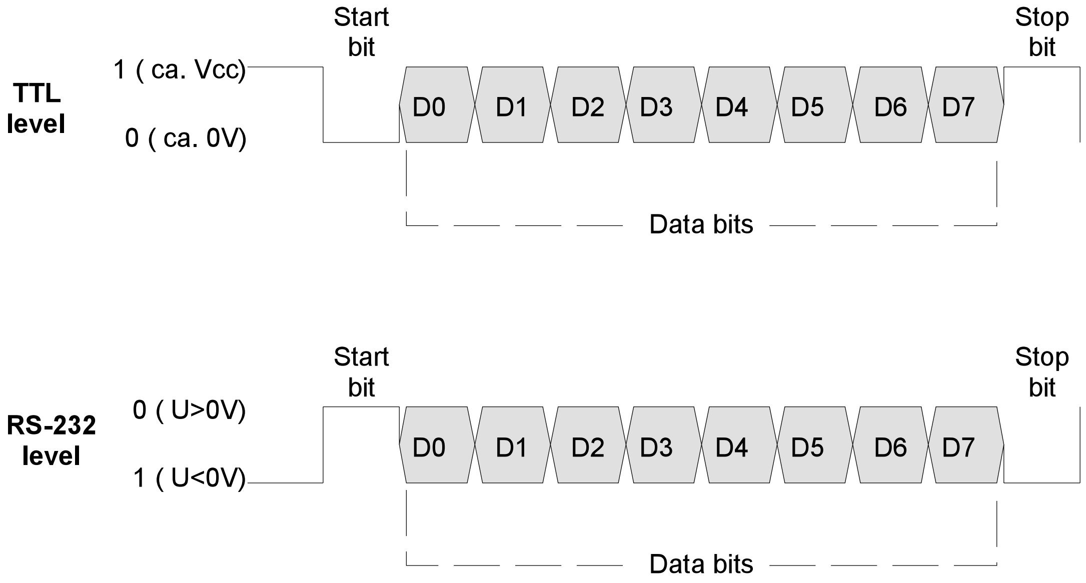


Figure 43: NMEA format (TTL and RS-232 level)

The different levels must be taken into consideration depending on whether the GPS receiver used has a TTL or RS-232 interface (Figure 43):

- In the case of a TTL level interface, a logical zero corresponds to approx. 0V and a logical one roughly to the operating voltage of the system (+3.3V ... +5V)
- In the case of an RS-232 interface a logical zero corresponds to a positive voltage (+3V ... +15V) and a logical one a negative voltage (-3V ... –15V).

If a GPS module with a TTL level interface is connected to an appliance with an RS-232 interface, a level conversion must be effected (see 8.3.4).

A few GPS modules allow the baud rate to be increased (up to 38400 bits per second).

Each GPS data set is formed in the same way and has the following structure:

$GPDTS,Inf_1,Inf_2, Inf_3,Inf_4,Inf_5,Inf_6,Inf_n*CS<CR><LF>

The function of the individual characters or character sets is explained in Table 8.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
DTS	Data set identifier (e.g. RMC)
Inf_1 bis Inf_n	Information with number 1 ... n (e.g. 175.4 for course data)
,	Comma used as a separator for different items of information
*	Asterisk used as a separator for the checksum
CS	Checksum (control word) for checking the entire data set
<CR><LF>	End of the data set: carriage return (<CR>) and line feed, (<LF>)

Table 8: Description of the individual NMEA DATA SET blocks

The maximum number of characters used must not exceed 79. For the purposes of determining this number, the start sign $ and end signs <CR><LF> are not counted.

The following NMEA protocol was recorded using a GPS receiver (Table 9):

$GPRMC,130303.0,A,4717.115,N,00833.912,E,000.03,043.4,200601,01.3,W*7D<CR><LF>
$GPZDA,130304.2,20,06,2001,,*56<CR><LF>
$GPGGA,130304.0,4717.115,N,00833.912,E,1,08,0.94,00499,M,047,M,,*59<CR><LF>
$GPGLL,4717.115,N,00833.912,E,130304.0,A*33<CR><LF>
$GPVTG,205.5,T,206.8,M,000.04,N,000.08,K*4C<CR><LF>
$GPGSA,A,3,13,20,11,29,01,25,07,04,,,,,1.63,0.94,1.33*04<CR><LF>
$GPGSV,2,1,8,13,15,208,36,20,80,358,39,11,52,139,43,29,13,044,36*42<CR><LF>
$GPGSV,2,2,8,01,52,187,43,25,25,074,39,07,37,286,40,04,09,306,33*44<CR><LF>
$GPRMC,130304.0,A,4717.115,N,00833.912,E,000.04,205.5,200601,01.3,W*7C<CR><LF>
$GPZDA,130305.2,20,06,2001,,*57<CR><LF>
$GPGGA,130305.0,4717.115,N,00833.912,E,1,08,0.94,00499,M,047,M,,*58<CR><LF>
$GPGLL,4717.115,N,00833.912,E,130305.0,A*32<CR><LF>
$GPVTG,014.2,T,015.4,M,000.03,N,000.05,K*4F<CR><LF>
$GPGSA,A,3,13,20,11,29,01,25,07,04,,,,,1.63,0.94,1.33*04<CR><LF>
$GPGSV,2,1,8,13,15,208,36,20,80,358,39,11,52,139,43,29,13,044,36*42<CR><LF>
$GPGSV,2,2,8,01,52,187,43,25,25,074,39,07,37,286,40,04,09,306,33*44<CR><LF>

Table 9: Recording of an NMEA protocol

8.2.1.2 GGA data set

The GGA data set (GPS Fix Data) contains information on time, longitude and latitude, the quality of the system, the number of satellites used and the height.

An example of a GGA data set:
$GPGGA,130305.0,4717.115,N,00833.912,E,1,08,0.94,00499,M,047,M,,*58<CR><LF>

The function of the individual characters or character sets is explained in Table 10.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
GGA	Data set identifier
130305.0	UTC positional time: 13h 03min 05.0sec
4717.115	Latitude: 47° 17.115 min
N	Northerly latitude (N=north, S= south)
00833.912	Latitude: 8° 33.912min
E	Easterly longitude (E= east, W=west)
1	GPS quality details (0= no GPS, 1= GPS, 2=DGPS)
08	Number of satellites used in the calculation
0.94	Horizontal Dilution of Precision (HDOP)
00499	Antenna height data (geoid height)
M	Unit of height (M= meter)
047	Height differential between an ellipsoid and geoid
M	Unit of differential height (M= meter)
,,	Age of the DGPS data (in this case no DGPS is used)
0000	Identification of the DGPS reference station
*	Separator for the checksum
58	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 10: Description of the individual GGA data set blocks

8.2.1.3 GLL data set

The GLL data set (geographic position – latitude/longitude) contains information on latitude and longitude, time and health.

Example of a GLL data set:
$GPGLL,4717.115,N,00833.912,E,130305.0,A*32<CR><LF>

The function of the individual characters or character sets is explained in Table 11.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
GLL	Data set identifier
4717.115	Latitude: 47° 17.115 min
N	Northerly latitude (N=north, S= south)
00833.912	Longitude: 8° 33.912min
E	Easterly longitude (E=east, W=west)
130305.0	UTC positional time: 13h 03min 05.0sec
A	Data set quality: A means valid (V= invalid)
*	Separator for the checksum
32	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 11: Description of the individual GGL data set blocks

8.2.1.4 GSA data set

The GSA data set (GNSS DOP and Active Satellites) contains information on the measuring mode (2D or 3D), the number of satellites used to determine the position and the accuracy of the measurements (DOP: Dilution of Precision).

An example of a GSA data set:

$GPGSA,A,3,13,20,11,29,01,25,07,04,,,,,1.63,0.94,1.33*04<CR><LF>

The function of the individual characters or sets of characters is decribed in Table 12.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
GSA	Data set identifier
A	Calculating mode (A= automatic selection between 2D/3D mode, M= manual selection between 2D/3D mode)
3	Calculating mode (1= none, 2=2D, 3=3D)
13	ID number of the satellites used to calculate position
20	ID number of the satellites used to calculate position
11	ID number of the satellites used to calculate position
29	ID number of the satellites used to calculate position
01	ID number of the satellites used to calculate position
25	ID number of the satellites used to calculate position
07	ID number of the satellites used to calculate position
04	ID number of the satellites used to calculate position
,,,,,	Dummy for additional ID numbers (currently not used)
1.63	PDOP (Position Dilution of Precision)
0.94	HDOP (Horizontal Dilution of Precision)
1.33	VDOP (Vertical Dilution of Precision)
*	Separator for the checksum
04	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 12: Description of the individual GSA data set blocks

8.2.1.5 GSV data set

The GSV data set (GNSS Satellites in View) contains information on the number of satellites in view, their identification, their elevation and azimuth, and the signal-to-noise ratio.

An example of a GSV data set:
$GPGSV,2,2,8,01,52,187,43,25,25,074,39,07,37,286,40,04,09,306,33*44<CR><LF>

The function of the individual characters or character sets is explained in Table 13.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
GSV	Data set identifier
2	Total number of GVS data sets transmitted (up to 1 ... 9)
2	Current number of this GVS data set (1 ... 9)
09	Total number of satellites in view
01	Identification number of the first satellite
52	Elevation (0° .... 90°)
187	Azimuth (0° ... 360°)
43	Signal-to-noise ratio in db-Hz (1 ... 99, null when not tracking)
25	Identification number of the second satellite
25	Elevation (0° .... 90°)
074	Azimuth (0° ... 360°)
39	Signal-to-noise ratio in dB-Hz (1 ... 99, null when not tracking)
07	Identification number of the third satellite
37	Elevation (0° .... 90°)
286	Azimuth (0° ... 360°)
40	Signal-to-noise ratio in db-Hz (1 ... 99, null when not tracking)
04	Identification number of the fourth satellite
09	Elevation (0° .... 90°)
306	Azimuth (0° ... 360°)
33	Signal-to-noise ratio in db-Hz (1 ... 99, null when not tracking)
*	Separator for the checksum
44	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 13: Description of the individual GSV data set blocks

8.2.1.6 RMC data set

The RMC data set (Recommended Minimum Specific GNSS) contains information on time, latitude, longitude and height, system status, speed, course and date. This data set is relayed by all GPS receivers.

An example of an RMC data set:
$GPRMC,130304.0,A,4717.115,N,00833.912,E,000.04,205.5,200601,01.3,W*7C<CR><LF>

The function of the individual characters or character sets is explained in Table 14.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
RMC	Data set identifier
130304.0	Time of reception (world time UTC): 13h 03 min 04.0 sec
A	Data set quality: A signifies valid (V= invalid)
4717.115	Latitude: 47° 17.115 min
N	Northerly latitude (N=north, S= south)
00833.912	Longitude: 8° 33.912 min
E	Easterly longitude (E=east, W=west)
000.04	Speed: 0.04 knots
205.5	Course: 205.5°
200601	Date: 20th June 2001
01.3	Adjusted declination: 1.3°
W	Westerly direction of declination (E = east)
*	Separator for the checksum
7C	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 14: Description of the individual RMC data set blocks

8.2.1.7 VTG data set

The VGT data set (Course over Ground and Ground Speed) contains information on course and speed.

An example of a VTG data set:
$GPVTG,014.2,T,015.4,M,000.03,N,000.05,K*4F<CR><LF>

The function of the individual characters or character sets is explained in Table 15.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
VTG	Data set identifier
014.2	Course 14.2° (T) with regard to the horizontal plane
T	Angular course data relative to the map
015.4	Course 15.4° (M) with regard to the horizontal plane
M	Angular course data relative to magnetic north
000.03	Horizontal speed (N)
N	Speed in knots
000.05	Horizontal speed (Km/h)
K	Speed in km/h
*	Separator for the checksum
4F	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 15: Description of the individual VTG data set blocks

8.2.1.8 ZDA data set

The ZDA data set (time and date) contains information on UTC time, the date and local time.

An example of a ZDA data set:

$GPZDA,130305.2,20,06,2001,,*57<CR><LF>

The function of the individual characters or character sets is explained in Table 16.

Field	Description
$	Start of the data set
GP	Information originating from a GPS appliance
ZDA	Data set identifier
130305.2	UTC time: 13h 03min 05.2sec
20	Day (00 … 31)
06	Month (1 … 12)
2001	Year
	Reserved for data on local time (h), not specified here
	Reserved for data on local time (min), not specified here
*	Separator for the checksum
57	Checksum for verifying the entire data set
<CR><LF>	End of the data set

Table 16: Description of the individual ZDA data set blocks

8.2.1.9 Calculating the checksum

The checksum is determined by an exclusive-or operation involving all 8 data bits (excluding start and stop bits) from all transmitted characters, including separators. The exclusive-or operation commences after the start of the data set ($ sign) and ends before the checksum separator (asterisk: *).

The 8-bit result is divided into 2 sets of 4 bits (nibbles) and each nibble is converted into the appropriate hexadecimal value (0 ... 9, A ... F). The checksum consists of the two hexadecimal values converted into ASCII characters.

The principle of checksum calculation can be explained with the help of a brief example:
The following NMEA data set has been received and the checksum (CS) must be verified for its correctness.
$GPRTE,1,1,c,0***07** (**07** is the checksum)

Procedure:

1. Only the characters between $ and * are included in the analysis: GPRTE,1,1,c,0
2. These 13 ASCII characters are converted into 8 bit values (see Table 17)
3. Each individual bit of the 13 ASCII characters is linked to an exclusive-or operation (N.B. If the number of ones is uneven, the exclusive-or value is one)
4. The result is divided into two nibbles
5. The hexadecimal value of each nibble is determined
6. Both hexadecimal characters are transmitted as ASCII characters to form the checksum

Character	**ASCII (8 bit value)**							
G	0	1	0	0	0	1	1	1
P	0	1	0	1	0	0	0	0
R	0	1	0	1	0	0	1	0
T	0	1	0	1	0	1	0	0
E	0	1	0	0	0	1	0	1
,	0	0	1	0	1	1	0	0
1	0	0	1	1	0	0	0	1
,	0	0	1	0	1	1	0	0
1	0	0	1	1	0	0	0	1
,	0	0	1	0	1	1	0	0
C	0	1	1	0	0	0	1	1
,	0	0	1	0	1	1	0	0
0	0	0	1	1	0	0	0	0
Exclusive-or value	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**
Nibble	0000				0111			
Hexadecimal value	0				7			
ASCII CS characters (meets requirements!)	**0**				**7**			

Direction to proceed

Table 17: Determining the checksum in the case of NMEA data sets

8.2.2 The DGPS correction data (RTCM SC-104)

The RTCM SC-104 standard is used to transmit correction values. RTCM SC-104 stands for "Radio Technical Commission for Maritime Services Special Committee 104" and is currently recognised around the world as the industry standard [xvi]. There are two versions of the RTCM Recommended Standards for Differential NAVSTAR GPS Service

- Version 2.0 (issued in January 1990)
- Version 2.1 (issued in January 1994)

Version 2.1 is a reworked version of 2.0 and is distinguished, in particular, by the fact that it provides additional information for real time navigation (Real Time Kinematic, RTK).

Both versions are divided into 63 message types, numbers 1, 2, 3 and 9 being used primarily for corrections based on code measurements.

8.2.2.1 The RTCM message header

Each message type is divided into words of 30 bits and, in each instance, begins with a uniform header comprising two words (WORD 1 and WORD 2). From the information contained in the header it is apparent which message type follows [xvii] and which reference station has determined the correction data (Figure 44 from [xviii]).

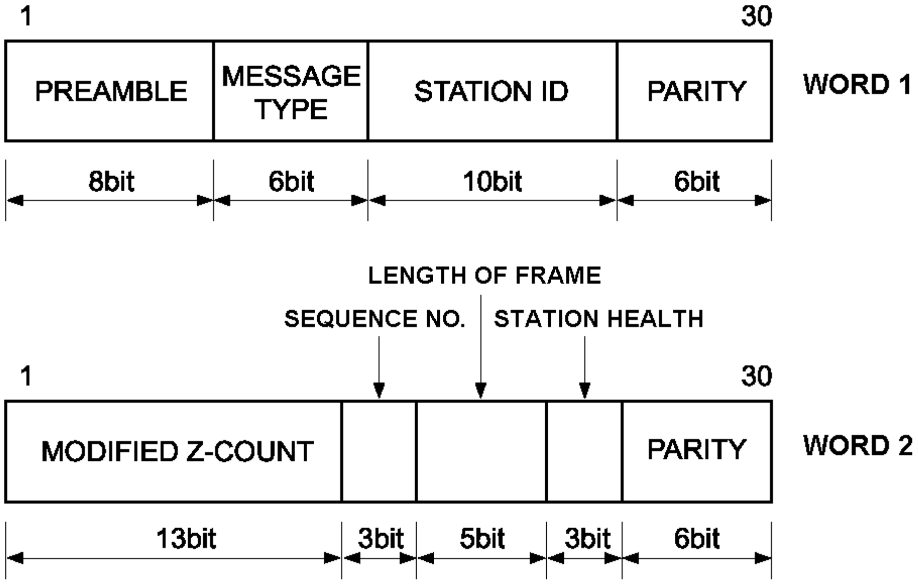


Figure 44: Construction of the RTCM message header

Contents	Name	Description
PREAMBLE	Preamble	Preamble
MESSAGE TYPE:	Message type	Message type identifier
STATION ID	Reference station ID No.	Reference station identification
PARITY	Error correction code	Parity
MODIFIED Z-COUNT	Modified Z-count	Modified Z-Count, incremental time counter
SEQUENCE NO.	Frame sequence No.	Sequential number
LENGTH OF FRAME	Frame length	Length of frame
STATION HEALTH	Reference station health	Technical status of the reference station

Table 18: Contents of the RTCM message header

The specific data content for the message type (WORD 3 ... WORD n) follows the header, in each case.

8.2.2.2 RTCM message type 1

Message type 1 transmits pseudo-range correction data (PSR correction data, range correction) for all GPS satellites visible to the reference station, based on the most up-to-date orbital data (ephemeris). Type 1 additionally contains the rate-of-change correction value (Figure 45, extract from [xix], only WORD 3 to WORD 6 is shown).

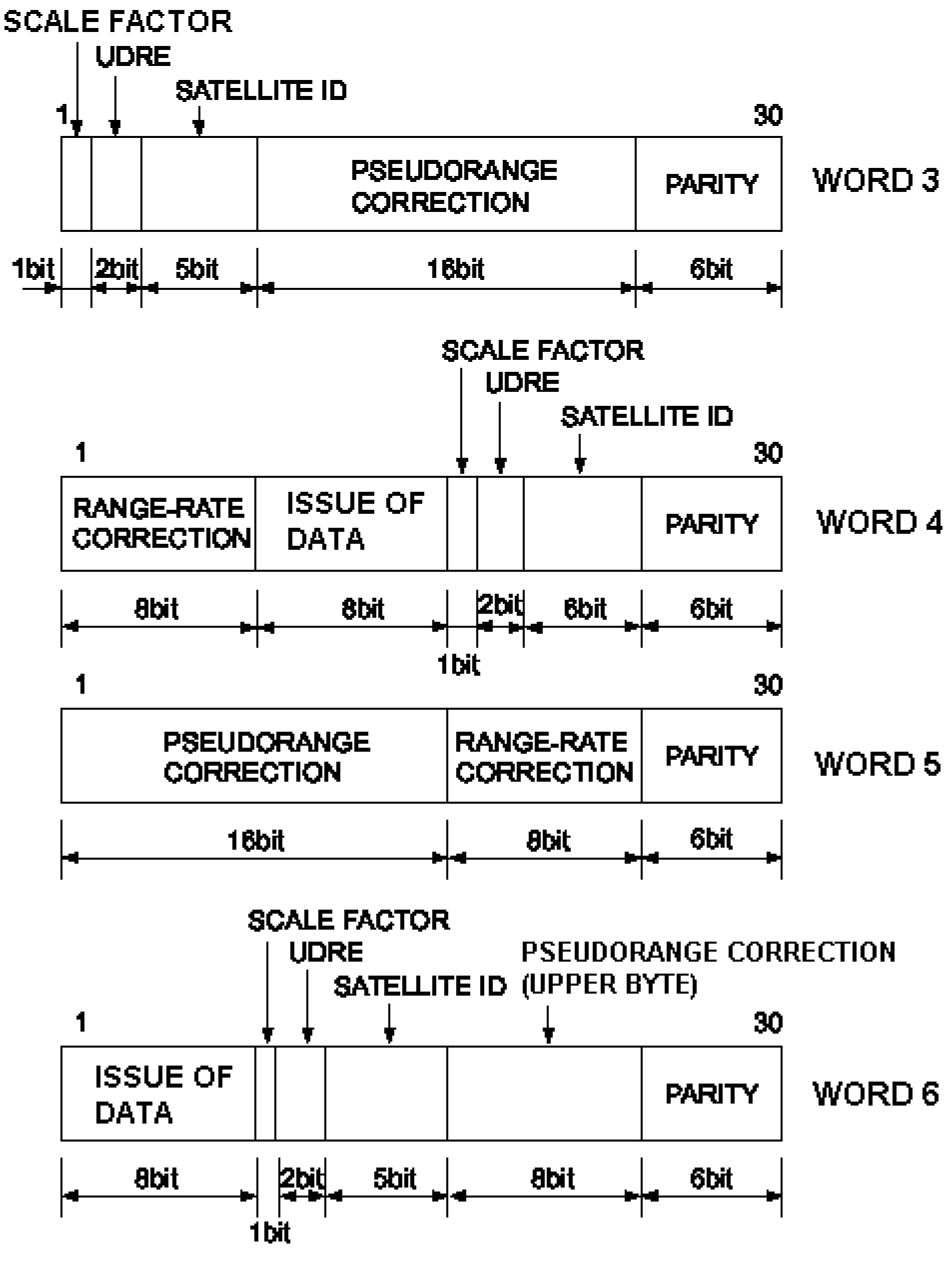


Figure 45: Construction of RTCM message type 1

Contents	Name	Description
SCALE FACTOR	Pseudo-range correction value scale factor	PSR scale factor
UDRE	User differential range error index	User differential range error index
SATELLITE ID	Satellite ID No.	Satellite identification
PSEUDORANGE CORRECTION	Pseudo-range correction value	Effective range correction
RANGE-RATE CORRECTION	Pseudo-range rate-of-change correction value	Rate-of-change of the correction data
ISSUE OF DATA	Data issue No.	Issue of data
PARITY	Error correction code	Check bits

Table 19: Contents of RTCM message type 1

8.2.2.3 RTCM message type 2 to 9

Message types 2 to 9 are distinguished primarily by their data content:

- **Message type 2** transmits delta PSR correction data, based on previous orbital data. This information is required whenever the GPS user has been unable to update his satellite orbital information. In message type 2, the difference between correction values based on the previous and updated ephemeris is transmitted.
- **Message type 3** transmits the three dimensional co-ordinates of the reference station.
- **Message type 9** relays the same information as message type 1, but only for a limited number of satellites (max. 3). Data is only transmitted from those satellites whose correction values change rapidly.

In order for there to be a noticeable improvement in accuracy using DGPS, the correction data relayed should not be older than approx. 10 to 60 seconds (different values are supplied depending on the service operator, the exact value also depends on the accuracy required, see also [xx]). Accuracy decreases as the distance between the reference and user station increases. Trial measurements using the correction signals broadcast by the LW transmitter in Mainflingen, Germany, (see section A 1.3) produced an error rate of 0.5 – 1.5 m within a radius of 250 km, and 1 – 3 m within a radius of 600 km [xxi].

8.3 Hardware interfaces

8.3.1 Antenna

GPS modules can either be operated with a passive or active antenna. Active antennae, i.e. with a built-in preamplifier (LNA: Low Noise Amplifier) are powered from the GPS module, the current being provided by the HF signal line. For mobile navigational purposes combined antennae (e.g. GSM/FM and GPS) are supplied. GPS antennae receive right-handed circular polarised waves.

Two types of antenna are obtainable on the market, Patch antennae and Helix antennae. Patch antennae are flat, generally have a ceramic and metallised body and are mounted on a metal base plate. In order to ensure a sufficiently high degree of selectivity, the base to Patch surface ratio has to be adjusted. Patch antennae are often cast in a housing (Figure 46), [xxii]).

Helix antennae are cylindrical in shape (Figure 47, [xxiii]) and have a higher gain than the Patch antennae.

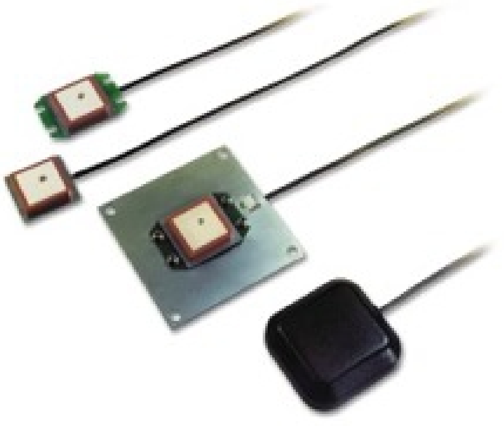


Figure 46: Open and cast Patch antennae

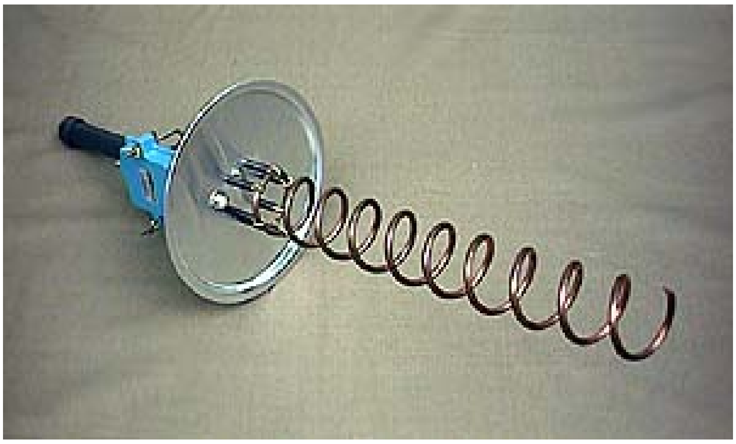


Figure 47: Basic structural shape of a Helix antennae

8.3.2 Supply

GPS modules must be powered from an external voltage source of 3.3V to 6 Volts. In each case, the power draw is very different.

8.3.3 Time pulse: 1PPS and time systems

Most GPS modules generate a time pulse every second, referred to as 1 PPS (1 pulse per second), which is synchronised to UTC. This signal usually has a TTL level (Figure 48).

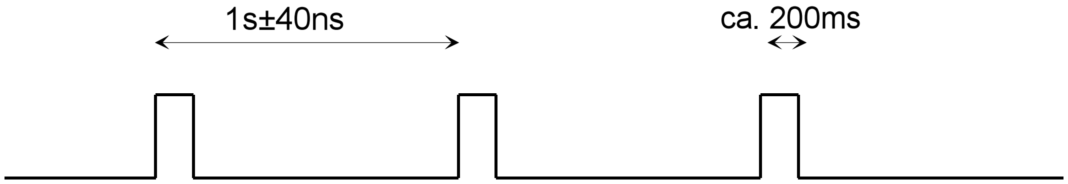


Figure 48: 1PPS signal

The time pulse can be used to synchronise communication networks (Precision Timing).

As time can play a fundamental part when GPS is used to determine a position, a distinction is drawn here between five important GPS time systems:

8.3.3.1 Atomic time (TAI)

The International Atomic Time Scale (Temps Atomique International) was introduced in order to provide a universal 'absolute' time scale that would meet various practical demands and at the same time also be of significance for GPS positioning. Since 1967, the second has been defined by an atomic constant in physics, the non-radioactive element Caesium ^{133}Cs being selected as a reference. The resonant frequency between the selected energy states of this atom has been determined at 9 192 631 770 Hz. Time defined in this way is therefore part of the SI system (Système International). The start of atomic time took place on 01.01.1958 at 00.00 hours.

8.3.3.2 Universal time co-ordinated (UTC)

UTC (Universal Time Coordinated) was introduced, in order to have a practical time scale that was oriented towards universal atomic time and, at the same time, adjusted to universal co-ordinated time. It is distinguished from TAI in the way the seconds are counted, i.e. UTC = TAI - n, where n = complete seconds that can be altered on 1st January or 1st June of any given year (leap seconds).

8.3.3.3 GPS time

General GPS system time is specified by a week number and the number of seconds within that week. The start date was Sunday, 6th January 1980 at 0.00 hours (UTC). Each GPS week starts in the night from Saturday to Sunday, the continuous time scale being set by the main clock at the Master Control Station. The time difference that arises between GPS and UTC time is constantly being calculated and appended to the navigation message.

8.3.3.4 Satellite time

Because of constant, irregular frequency errors in the atomic clocks on board the GPS satellites, individual satellite time is at variance with GPS system time. The satellite clocks are monitored by the control station and any apparent time difference relayed to Earth. Any time differences must be taken into account when conducting local GPS measurements.

8.3.3.5 Local time

Local time is the time referred to within a certain area. The relationship between local time and UTC time is determined by the time zone and regulations governing the changeover from normal time to summertime.

Example of a time frame (Table 20) on 21st June 2001 (Zurich)

Time basis	Time displayed (hh:min:sec)	Difference n to UTC (sec)
Local time	08:31:26	7200 (=2h)
UTC	06:31:26	0
GPS	06:31:39	+13
TAI	06:31:58	+32

Table 20: Time systems

The interrelationship of time systems (valid for 2001):

TAI – UTC = +32sec
GPS – UTC = +13sec
TAI – GPS = +19sec

8.3.4 Converting the TTL level to RS-232

8.3.4.1 Basics of serial communication

The purpose of the RS-232 interface is mainly

- to link computers to each other (mostly bidirectional)
- to control serial printers
- to connect PCs to external equipment, such as GSM modems, GPS receivers, etc.

The serial ports in PCs are designed for asynchronous transfer. Persons engaged in transmitting and receiving operations must adhere to a compatible transfer protocol, i.e. an agreement on how data is to be transferred. Both partners must work with the same interface configuration, and this will affect the rate of transfer measured in baud. The baud rate is the number of bits per second to be transferred. Typical baud rates are 110, 150, 300, 600, 1200, 2400, 4800, 9600, 19200 and 38400 baud, i.e. bits per second. These parameters are laid down in the transfer protocol. In addition, agreement must be reached by both sides on what checks should be implemented regarding the ready to transmit and receive status.

During transmission, 7 to 8 data bits are condensed into a data word in order to relay the ASCII codes. The length of a data word is laid down in the transfer protocol.

The beginning of a data word is identified by a start bit, and at the end of every word 1 or 2 stop bits are appended.

A check can be carried out using a parity bit. In the case of even parity, the parity bit is selected in such a way that the total number of transferred data word »1 bits« is even (in the case of uneven parity there is an uneven number). Checking parity is important, because interference in the link can cause transmission errors. Even if one bit of a data word is altered, the error can be identified using the parity bit.

8.3.4.2 Determining the level and its logical allocation

Data is transmitted in inverted logic on the TxD and RxD lines. T stands for transmitter and R for receiver.

In accordance with standards, the levels are:

- Logical 0 = positive voltage, transmit mode: +5..+15V, receive mode:+3..+15V
- Logical 1 = negative voltage, transmit mode: -5..-15V, receive mode -3..-15V

The difference between the minimum permissible voltage during transmission and reception means that line interference does not affect the function of the interface, provided the noise amplitude is below 2V.

Converting the TTL level of the interface controller (UART, universal asynchronous receiver/ transmitter) to the required RS-232 level and vice versa is carried out by a level converter (e.g. MAX3221 and many more besides). The following figure (Figure 49) illustrates the difference between TTL and RS-232 levels. Level inversion can clearly be seen.

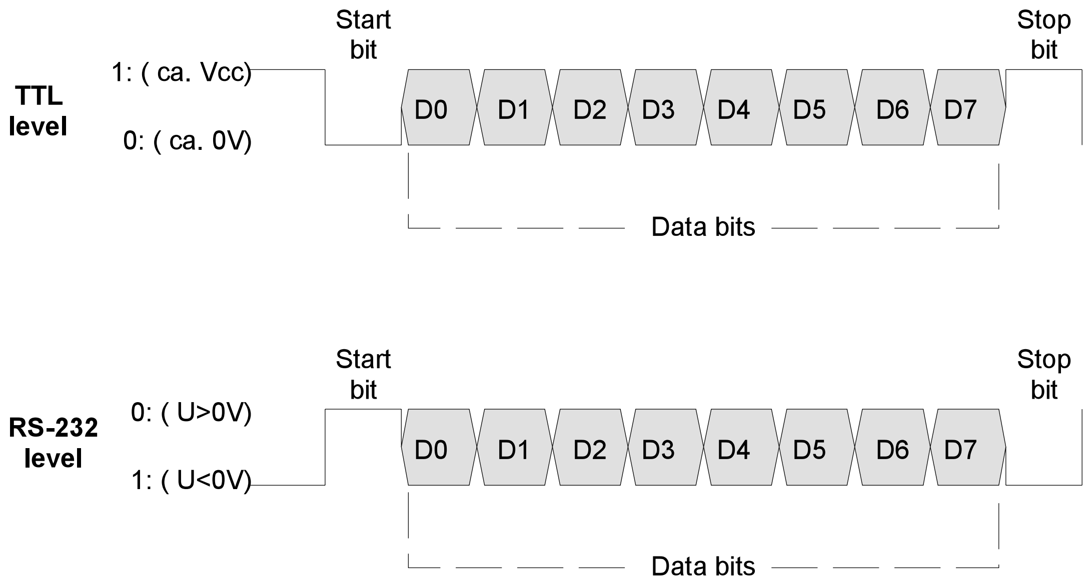


Figure 49: Difference between TTL and RS-232 levels

8.3.4.3 Converting the TTL level to RS-232

Many GPS receivers and GPS modules only make serial NMEA and proprietary data available using TTL levels (approx. 0V or approx. Vcc = +3.3V or +5V). It is not always possible to evaluate this data directly through a PC, as a PC input requires RS 232 level values.

As a circuit is needed to carry out the necessary level adjustment, the industry has developed integrated circuits specifically designed to deal with conversion between the two level ranges, to undertake signal inversion, and to accommodate the necessary equipment to generate negative supply voltage (by means of built-in charge pumps).

A complete bidirectional level converter that uses a "Maxim MAX3221" [xxiv] is illustrated on the following circuit diagram (Figure 50). The circuit has an operational voltage of 3V ... 5V and is protected against voltage peaks (ESD) of ±15kV. The function of the C1 ... C4 capacitors is to increase or invert the voltage.

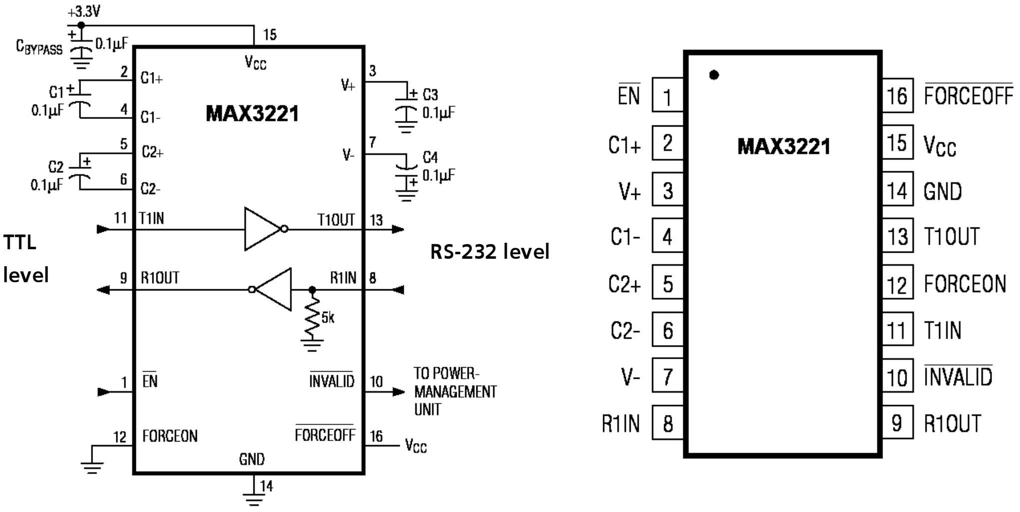


Figure 50: Block diagram pin assignment of the MAX32121 level converter

The following test circuit (Figure 51) clearly illustrates the way in which the modules function. In the case of this configuration, a TTL signal (0V ... 3.3V) is applied to line T_IN. The inversion and voltage increase to ±5V can be seen on lines T_OUT and R_IN of the RS-232 output.

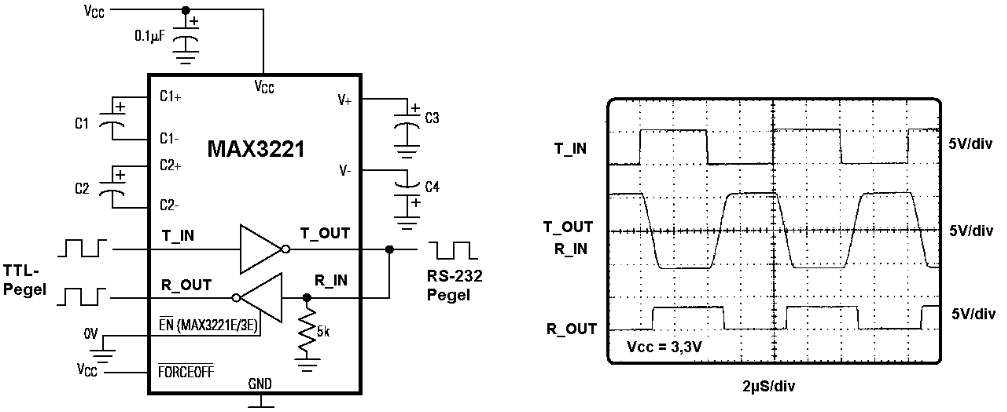


Figure 51: Functional test on the MAX3221 level converter

9 GPS RECEIVERS

If you would like to . . .

- know how a GPS receiver is constructed
- understand why several stages are necessary to reconstruct GPS signals
- know how an HF stage functions
- know how the signal processor functions
- understand how both stages interact
- know how a receiver module functions

then this chapter is for you!

9.1 Basics of GPS handheld receivers

A GPS receiver can be divided into the following main stages (Figure 52).

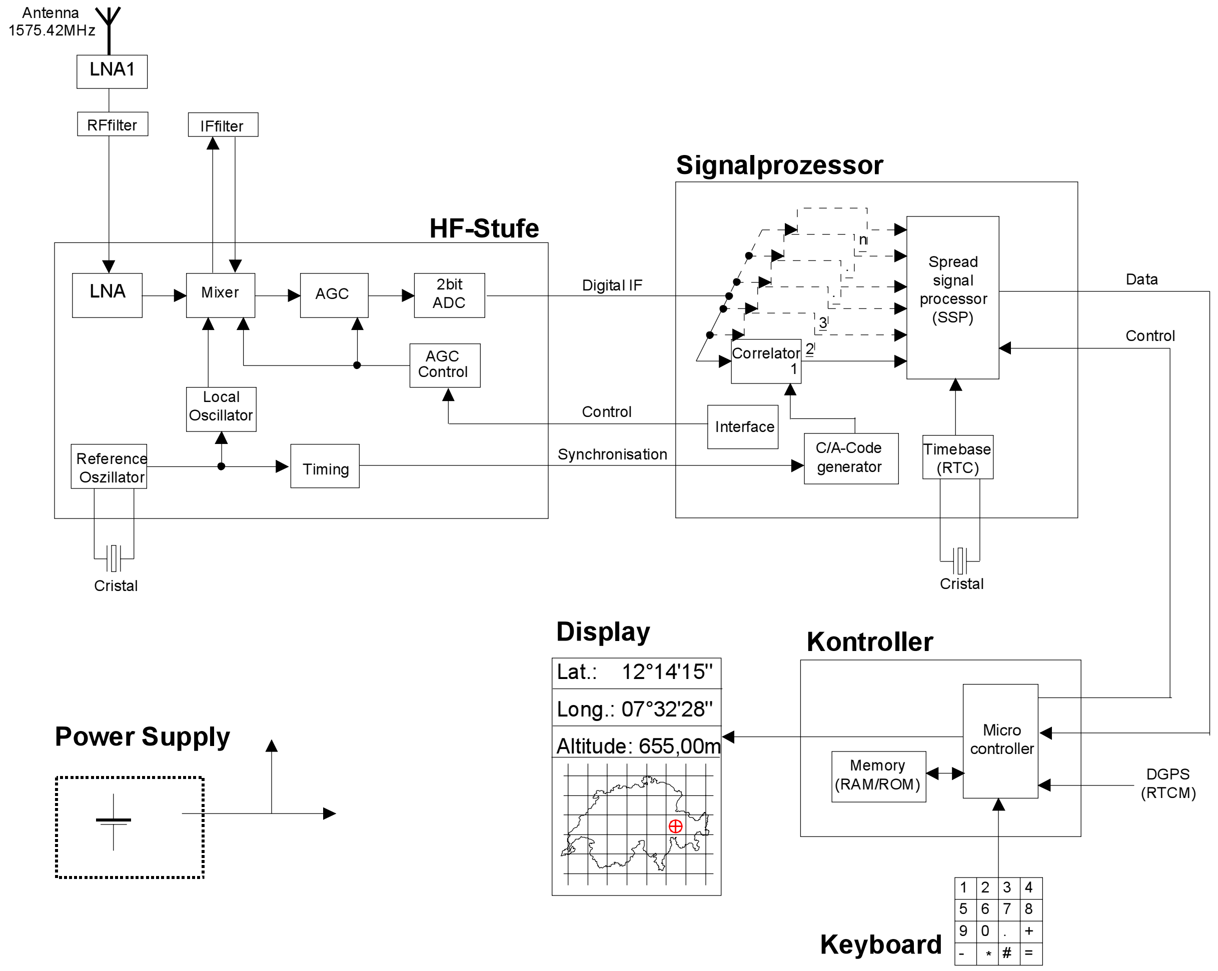


Figure 52: Simplified block diagram of a GPS receiver

- **Antenna**: The antenna receives extremely weak satellite signals on a frequency of 1572.42MHz. Signal output is around –163dBW. Some (passive) antennae have a 3dB gain.
- **LNA 1:** This low noise amplifier (LNA) amplifies the signal by approx. 15 ... 20dB.

- **HF filter:** The GPS signal bandwith is approx. 2MHZ. The HF filter reduces the affects of signal interference. The HF stage and signal processor actually represent the special circuits in a GPS receiver and are adjusted to each other.
- **HF stage:** The amplified GPS signal is mixed with the frequency of the local oscillator. The filtered IF signal is maintained at a constant level in respect of its amplitude and digitalised via Amplitude Gain Control (AGC)
- **IF filter:** The intermediate frequency is filtered out using a bandwidth of 2MHz. The image frequencies arising at the mixing stage are reduced to a permissible level.
- **Signal processor:** Up to 16 different satellite signals can be correlated and decoded at the same time. Correlation takes place by constant comparison with the C/A code. The HF stage and signal processor are simultaneously switched to synchronise with the signal. The signal processor has its own time base (Real Time Clock, RTC). All the data ascertained is broadcast (particularly signal transit time to the relevant satellites determined by the correlator), and this is referred to as source data. The signal processor can be offset by the controller via the control line to function in various operating modes.
- **Controller:** Using the source data, the controller calculates position, time, speed and course etc. It controls the signal processor and relays the calculated values to the display. Important information (such as ephemeris, the most recent position etc.) are decoded and saved in RAM. The program and the calculation algorithms are saved in ROM.
- **Keyboard:** Using the keyboard, the user can select, which co-ordinate system he wishes to use and which parameters (e.g. number of visible satellites) should be displayed.
- **Display:** The position calculated (longitude, latitude and height) must be made available to the user. This can either be displayed using a 7-segment display or shown on a screen using a projected map. The positions determined can be saved, whole routes being recorded.
- **Current supply:** The power supply delivers the necessary operational voltage to all levels of electronic componentry.

9.2 GPS receiver modules

9.2.1 Basic design of a GPS module

GPS modules have to evaluate weak antenna signals from at least four satellites, in order to determine a correct three-dimensional position. A time signal is also often emitted in addition to longitude, latitude and height. This time signal is synchronised with UTC (Universal Time Coordinated). From the position determined and the exact time, additional physical variables, such as speed and acceleration can also be calculated. The GPS module issues information on the constellation, satellite health, and the number of visible satellites etc.

Figure 53 shows a typical block diagram of a GPS module.

The signals received (1575.42 MHz) are pre-amplified and transformed to a lower intermediate frequency. The reference oscillator provides the necessary carrier wave for frequency conversion, along with the necessary clock frequency for the processor and correlator. The analogue intermediate frequency is converted into a digital signal by means of a 2-bit ADC.

Signal transit time from the satellites to the GPS receiver is ascertained by correlating PRN pulse sequences. The satellite PRN sequence must be used to determine this time, otherwise there is no correlation maximum. Data is recovered by mixing it with the correct PRN sequence. At the same time, the useful signal is amplified above the interference level [XXV]. Up to 16 satellite signals are processed simultaneously. The control and generation of PRN sequences and the recovery of data is carried out by a signal processor. Calculating and saving the position, including the variables derived from this, is carried out by a processor with a memory facility.

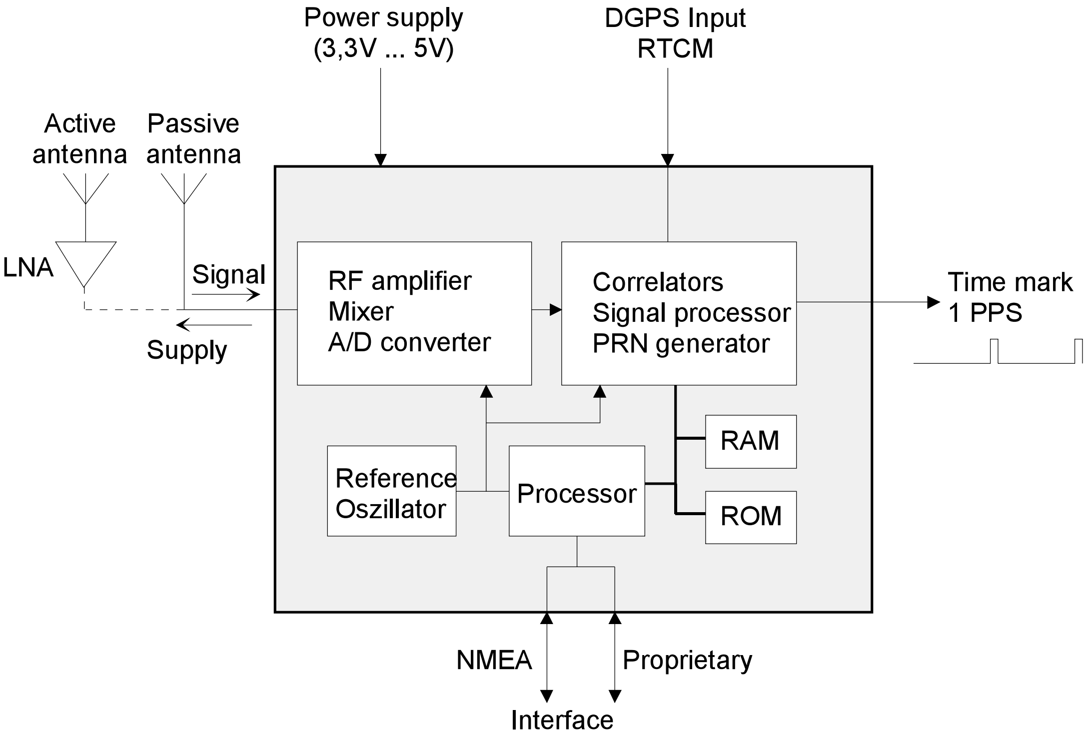


Figure 53: Typical block diagram of a GPS module

10 GPS APPLICATIONS

If you would like to . . .

- know what variables can be determined using GPS
- know what applications are possible with GPS
- know how time is determined to precise values

then this chapter is for you!

10.1 Introduction

Using the **G**lobal **P**ositioning **S**ystem (GPS, a process used to establish a position at any point on the globe) the following two values can be determined anywhere on Earth:

- One's exact location (longitude, latitude and height co-ordinates) accurate to within a range of 20 m to approx. 1mm
- The precise time (world time, Universal Time Coordinated, UTC) accurate to within a range of 60ns to approx. 1ns.

Various additional variables can be derived from the three-dimensional position and the exact time, such as:

- speed
- acceleration
- course
- local time
- range measurements

The traditional fields of application for GPS are surveying, shipping and aviation. However, the market is currently enjoying a surge in demand for electronic car navigation systems. The reason for this enormous growth in demand is the motor industry, which is hoping to make better use of the road traffic network by utilising this equipment. Applications, such as Automatic Vehicle Location (AVL) and the management of vehicle fleets also appear to be on the rise. GPS is also being increasingly utilised in communication technology. For example, the precise GPS time signal is used to synchronise telecommunications networks around the world. From 2001, the US Federal Communications Commission (FCC) is demanding that, when Americans ring 911 in an emergency, their position can automatically be located to within approx. 125m. This law, known as E-911 (Enhanced 911), means that mobile telephones will have to be upgraded with this new technology.

In the leisure industry too, the use of GPS is becoming increasingly established. Whether on a hike, out hunting, touring on one's Mountain Bike, or surfing across Lake Constance in Southern Germany, a GPS receiver provides good service in any location.

Basically, GPS can be used anywhere where satellite signal reception is possible.

10.2 Description of the various applications

GPS aided navigation and positioning is used in many sectors of the economy, as well as in science, technology, tourism, research and surveying. The (D)GPS process can be employed wherever three-dimensional geodata has a significant role to play. A few important sectors are detailed below.

10.2.1 Science and research

GPS has readily found itself a place in archaeology ever since this branch of science began to use aerial and satellite imaging. By combining GIS (Geographic Information Systems) with satellite and aerial photography, as well as GPS and 3D modelling, it has been possible to answer some of the following questions.

- What conclusions regarding the distribution of cultures can be made based on finds?
- Is there a correlation between areas favouring the growth of certain arable plants and the spread of certain cultures?
- What sort of blending and intermingling of attributes enable conclusions to be drawn regarding the probable furthest most extent of a culture?
- What did the landscape look like in this vicinity 2000 years ago?

Geometricians use (D)GPS, in order to carry out surveys (satellite geodesy) quickly and efficiently to within an accuracy of a millimeter. For geometricians, the introduction of satellite-based surveying represents a quantum leap comparable to that between the abacus and the computer. The applications are endless, ranging from surveying properties, streets, railway lines and rivers to even charting the ocean depths, conducting Land Register surveys, carrying out deformation measurements and monitoring landslides etc.

In land surveying, GPS has virtually become an exclusive method for pinpointing sites in basic networks. Everywhere around the world, continental and national GPS networks are emerging that, in conjunction with the global ITRF, provide homogenous and highly accurate networks of points for density and point to point measurements. At a regional level, the number of tenders to set up GPS networks as a basis for geo-information systems and cadastral land surveys is growing.

Already today, GPS has an established place in photogrammetry. Apart from determining co-ordinates for ground reference points, GPS is regularly used to determine aerial survey navigation and camera co-ordinates in aero-triangulation. Using this method, over 90% or so of ground reference points can be dispensed with. Future remote reconnaissance satellites will also have GPS receivers, so that the evaluation of data for the production and updating of maps in underdeveloped countries, is made easier.

In hydrography, GPS can be used to determine the exact height of the survey boat, in order to facilitate the arrangement of vertical measurements on a clearly defined height reference surface. The expectation is that operational methods in this field will be available in the near future.

Other possible areas of application for GPS are:

- Archaeology
- Seismology (geophysics)
- Glaciology (geophysics)
- Geology (mapping)
- Surveying deposits (mineralogy, geology)
- Physics (flow measurements, time standardisation measurement)
- Scientific expeditions
- Engineering sciences (e.g. shipbuilding, general construction industry)
- Cartography
- Geography
- Geo-information technology
- Forestry and agricultural sciences
- Landscape ecology
- Geodesy
- Aerospace sciences

10.2.2 Commerce and industry

It is clear that road traffic will continue to be the biggest market for GPS. Out of a total market value estimated at 60 billion US-$ by 2005, 21.6 billion alone will be allocated to road traffic and 10.6 billion to telecommunications technology [xxvi]. A vehicle will have a computer with a screen, so that an appropriate map showing your position will be displayed no matter where you are. You will be able to select the best route to your destination. When there are traffic jams you will be able to find alternative routes without difficulty and the computer will calculate your journey time and the amount of fuel needed to get there.

Vehicle navigation systems will direct the driver to his or her destination with visually displayed directions and spoken recommendations. Using the requisite maps stored on CD-ROM, and position estimates based on GPS, the system will search for possible itineraries taking into account the most favourable routes,

GPS is already used as a matter of course in conventional navigation (aviation and shipping). Many trains are equipped with GPS receivers that relay the train's position to stations down the line. This enables staff to inform passengers of the arrival time of a train.

GPS can be used both for locating cars and as an anti-theft device. Security vans, limousines and lorries with valuable or hazardous loads etc. will be fitted with GPS, an alarm automatically being set off, if the vehicle deviates from its prescribed route. The alarm can, of course, be operated by the driver at the press of a button. Anti-theft devices will be fitted with GPS receivers, allowing an electronic vehicle immobiliser to be activated as soon as the monitoring centre receives a signal (e.g. when a subscriber's car sends a signal to the centre).

An additional function that can be performed by GPS is in the area of emergencies. This idea has already been developed as far as the marketing stage. A GPS receiver is connected to a crash sensor and in an emergency a signal is sent to an emergency call centre that knows precisely in which direction the vehicle was travelling and its current whereabouts. As a result, the consequences of an accident can be made less severe and other road users can be given greater advance warning.

As with all safety critical applications, where human life is dependent on technology functioning correctly, orbital operations too represent an area where precautions need to be taken against system failure. Back-up normally comes from equipment made redundant by new technology. In ideal situations, information for systems performing the same task comes from independent sources. Particularly successful solutions not only provide an error message, but also a display warning the user that the data shown may no longer be sufficiently reliable. At the same time, the system switches to another sensor as a data source. These systems monitor themselves, as it were. All this has been made possible by the miniturisation of electronic components, by their enormously increased performance and by hardware prices plummeting.

Other possible uses for GPS include:

- Exploration of geological deposits
- Remediation of landfill sites
- Development of open-cast mining
- Positioning of drill platforms
- Laying pipelines (geodesy in general)
- Extensive storage sites
- Automatic container movements
- Transport companies, logistics in general (aircraft, water-borne craft and road vehicles)
- Railways
- Geographical tachographs
- Fleet management
- Navigation systems

10.2.3 Agriculture and forestry

For the forestry sector too, there are many conceivable GPS applications. The USDA (United States Department of Agriculture) Forest Service GPS Steering Committee 1992, has identified over 130 possible applications in this field.

Examples of some these applications are briefly detailed below:

- Optimisation of round timber transportation: By equipping commercial vehicle fleets with on-board computers, as well as GPS, and remote data transfer facilities, the vehicles can be directed efficiently from a central operations unit.
- Use in inventory management: Manual identification prior to harvesting the wood is made redundant by the navigation system. For the foresters and workers on site, GPS can be used as a tool for carrying out processing instructions.
- Use in the field of soil conservation: By using GPS, the frequency with which remote tracks are used (dirt tracks for removing the harvested wood) can be identified. Also, a reliable search can be conducted to find such tracks.
- Management of small private woods: In woodland areas divided up into small parcels of land, cost-effective, highly mechanised harvesting processes can be employed using GPS, allowing additional quantities of wood to be transported.

GPS makes a contribution to precision farming in the form of area administration, and the mapping of sites in terms of yield and application potential. In a precision farming system, combine harvester yields are recorded by GPS and processed initially into specific partial plots on digital maps. Soil samples are also located with the help of GPS and added to the system. Analysis of these entries then serves to establish the amount of manure that needs to be applied to each point in the plot. The application maps are converted into a form that the on-board computer can process and are then transferred to this computer by means of memory boards. In this way, optimal operational practises can be devised over a long period of time that can offer a high savings potential and provide an initial attempt at nature conservation.

Other possible uses for GPS include:

- Use and planning of areas
- Monitoring of fallow land
- Planning and managing of plantations
- Use of harvesting equipment
- Scattering seeds and spreading fertiliser
- Optimising wood-felling operations
- Pest control
- Mapping blighted areas

10.2.4 Communications technology

Synchronising computer clocks to a uniform time in a distributed computer environment is vital. A highly accurate reference clock used to receive GPS satellite signals along with Network Time Protocol (NTP), specified in RFC 1305, forms the basis for this synchronisation

Other possible uses for GPS include:

- Synchronisation of system time-staggered message transfer
- Synchronisation in common frequency radio networks

10.2.5 Tourism / sport

GPS receivers are often used at competitive gliding and hang-gliding events as an infallible method of recording times.

People who have got into difficulties at sea or in the mountains can be located using GPS (SAR: Save and Rescue).

Other possible uses for GPS include:

- Route planning and selecting points of particular significance (natural monuments, culturally historic monuments)
- Orientiering in general (training routes)
- Outdoor activities and trekking
- Sporting activities

10.2.6 Military

GPS is used anywhere where combatants, vehicles, aircraft and guided missiles are deployed in unfamiliar terrain. GPS is also suitable for marking the position of minefields and underground depots, as it enables a location to be determined and found again without any great difficulty. As a rule, the more accurate, encrypted GPS signal (PPS) is used for military applications, and can only be used by authorised agencies.

10.2.7 Time measurement

GPS provides us with the opportunity of measuring time exactly on a global basis. Right around the world "time" (UTC Universal Time Coordinated) can be accurately determined to within 1 ... 60 ns. Measuring time with GPS is a lot more accurate than with so-called radio clocks, which are unable to compensate for signal transit time between the transmitter and the receiver. If, for example, the receiver is 300 km from the radio clock transmitter, signal transit time already accounts for 1ms, which is 10,000 times "more inaccurate" than time measured by a GPS receiver. Globally precise time measurements are necessary for synchronising control and communications facilities, for example.

The most usual method today of making precision time comparisons between clocks in different places is "common-view" comparison with the help of Global Positioning System (GPS) satellites. Institutes that wish to compare clocks measure the same GPS satellite signals at the same time in different places and calculate the time difference between the local clocks and GPS system time. As a result of the difference in measurement at two different places, the difference between the clocks at the two institutes can be determined. Because this involves a differential process, GPS clock status is irrelevant. Time comparisons between the PTB and time institutes are made in this way throughout the world. The PTB atomic clock status, determined with the help of GPS, is also relayed to the International Bureau for Weights and Measures (BIPM) in Paris for calculating the international atomic time scales TAI and UTC.

APPENDIX

A.1 DGPS services

A.1.1 Introduction

The reference receiver receives satellite signals and can immediately calculate the difference between the measured and actual distance. This difference is relayed to all surrounding user receivers via an appropriate communications link (LW, SW, VHF, radio, GSM, satellite communication ...). When the user receiver uses the corrected data, it can correct the measured range to all satellites by the amount of the difference. In this way, the effects of SA (SA was switched off on 1st May 2000) and the ionosphere and troposphere can be massively reduced. The Swiss National Topographical Institute offers such a DGPS service. The correction data is broadcast over the VHF or GSM network. In Germany, there is a DGPS service that broadcasts the correction data on LW via the Mainflingen transmitter (near Frankfurt-am-Main). In both instances, accuracy to within a few meters is achieved.

In Europe, correction signals are received by various public DGPS services. Some of these services have already been introduced, others are about to be launched. One thing all these services have in common is that, in contrast to GPS, they make a charge. Either an annual licence fee is levied or a one-off charge is made when the DGPS receiver is purchased.

A.1.2 Swipos-NAV (RDS or GSM)

There is a service that operates under the name of Swipos-NAV (Swiss Positioning Service) that distributes the correction data via RDS or GSM. The Radio Data System (RDS) is a European standard for the distribution of digital data over the VHF broadcasting network (FM, 87-108 MHz). RDS was developed to provide road users with traffic information via VHF [xxvii]. The RDS data is modulated to the FM carrier wave at a frequency of 57 kHz, the user needing an RDS decoder to extract the DGPS correction values. The RDS-GPS service is offered by the Federal Office for National Topography [xxviii] in conjunction with SRG. At present, FM transmitters, in particular, are active from Lake Geneva, across the 'Mittelland' region to Lake Constance, but further expansion throughout Switzerland is planned for the summer of 1999. In order to ensure good reception, there needs to be visible contact with a VHF transmitter. Users of this service can either pay an annual subscription or a one-off fee. The service is offered at two levels of accuracy.

- 1 - 2 m precision (for 95% of all measurements)
- 2 - 5 m precision (for 95% of all measurements)

A.1.3 AMDS

AMDS (Amplituden Moduliertes Daten System – amplitude modulated data system) is used to transmit digital data on medium and long-wave using existing broadcasting transmitters. The data is phase modulated. In the 'Mittelland' region of Switzerland at present signals can be received, in particular, from the Beromünster transmitter (MW, 531 kHz) and the German Rohrdorf transmitter (MW, 666 kHz). An extension of the Ceneri transmitter is currently being planned. Data is broadcast over an area of 600 – 1000 km. The service is operated in Switzerland by Terra Vermessungen AG [xxix]. After extensive trials, a regular service came on line in January 1999 with plans to charge a one-off fee.

A.1.4 SAPOS

SAPOS [xxx] (Satellitenpositionierungsdienst der deutschen Landesvermessung – Satellite Positioning Service supplied by the German National Survey Office) is a permanently operated, multi-functional DGPS service. It is highly reliable and available throughout Germany. A network of GPS reference stations forms the basis of the system. The ARD public broadcasting organisation, long-wave (Telekom), GSM and SAPOS's own 2-Meter band are offered as a standard for real time measurements. VHF media broadcasting and long-wave have long been available nationally for the EPS service sector, and in the 2-Meter band a total of 9 frequencies have been available to AdV [xxxi] (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland – a working group responsible for the administration of surveys carried out in the regional states of the Federal Republic of Germany) on a nationwide basis.

SAPOS comprises four areas of service with differing characteristics and precision:

- SAPOS EPS – real time positioning service
- SAPOS HEPS – ultra-precise real time positioning service
- SAPOS GPPS – Geodetic precision positioning service
- SAPOS GHPS – Geodetic high precision positioning service

Both EPS and HEPS are usable in real time.

In VHF broadcasts the signals are transmitted in a format known as RASANT (Radio Aided Satellite Navigation Technique). The RASANT correction data format is a conversion of RTCM 2.0 correction data for transmission over the Radio Data System (RDS) of VHF radio broadcasting.

A.1.5 ALF

ALF (Accurate Positioning by Low Frequency) broadcasts the correction values with an output of 50 kW von Mainflingen (Frankfurt-am-Main). The long-wave transmitter DCF42 (LW, 122.5 kHz) broadcasts its correction values over an area of 600 – 1000 km and can therefore be received in the 'Mittelland' region of Switzerland. The upper side band (OSB) is phase modulated (Bi-Phase-Shift-Keying, BPSK). The service is offered by the Federal Office for Cartography and Geodesy [xxxii] in co-operation with Deutsche Telekom AG (DTAG) [xxxiii]. The user pays a one-off fee when purchasing the decoder. Due to the propagation characteristics of long-wave, the correction data can be received despite shadowing.

A.1.6 dGPS

Austria has been covered nationally since the summer of 1998 with a positional accuracy better than 1 Meter [xxxiv]. The service comprises 8 reference stations and is still being expanded. It has even been possible since the summer of 2000 to achieve an accuracy of a few centimeters throughout Austria.

Data from the stations is relayed by Austrian Broadcasting via 18 main transmitter complexes and more than 250 converters. Correction data is broadcast by the data transmission system DARC (Data Radio Channel) over the Ö1 network. DARC is a data transmission system that relays digital data packets (e.g. images) as a VHF radio signal using the existing ORF infrastructure (transmitter, lines).

Due to the different demands made by the various individual applications, three different levels of accuracy are offered:

- guaranteed accuracy of less than 10 cm
- guaranteed accuracy of less than 1 m
- guaranteed accuracy of less than 10 m

A.1.7 Radio Beacons

Radio beacons are installed right around the world, principally along the coasts, relaying DGPS correction signals on a frequency of approx. 300kHz. The signal bit rate varies between 100 and 200 bits per second depending on the transmitter.

A.1.8 Omnistar and Landstar

Several geo-stationary satellites transmit correction data to Europe continuously. Two different services are available under the names of Omnistar and Landstar. Omnistar belongs to the Fugro Group [xxxv] and Landstar to Racal Survey [xxxvi]. Omnistar and Landstar transmit their information to Earth in the L-band (1-2 GHz). The corresponding reference stations are distributed throughout Europe. From the perspective of Switzerland, these geo-stationary satellites are located to the south approx. 35-38° above the horizon, and they must be visible, in order to establish radio contact. The system operators generally charge an annual fee.

A.1.9 EGNOS

EGNOS [xxxvii] (European Geo-stationary Navigation Overlay System) is a satellite-based augmentation system for existing GPS and Glonass satellite navigation systems. A European network of GPS/Glonass receivers has been built up to receive the corresponding satellite signals and relay these to central data processing stations. The signals received at these data processing stations are evaluated taking into account the exact known position of the receiving stations. In this way, correction data can be determined that is ultimately broadcast to users via geo-stationary communications satellites. With the help of these corrections positional accuracy of around 7 m can initially be achieved. In addition, a level of data integrity is attained that enables instrument approaches to be made in aviation.

Three such systems are currently under construction around the world: the American WAAS (Wide Area Augmentation System), the Japanese MSAS (MTSAT based Augmentation System) and the European EGNOS system. The three systems should be compatible with each other.

According to current planning, it is anticipated that the system will enter service in its initial stage of development by 2002/2003.

A.1.10 WAAS

The North-American WAAS system (**W**ide **A**rea **A**ugmentation **S**ystem) is a network of approx. 25 ground reference stations (WRS, **W**ide Area Ground **R**eference **S**tation) that receive GPS signals. They have been surveyed exactly in terms of their position. Each reference station determines actual and target pseudo-range deviation. The error signals are relayed to a master station WMS (**W**ide Area **M**aster **S**tation). The WMS's calculate the differential signals and monitor the integrity of the GPS system. The precisely processed DGPS correction values are transmitted to two geo-stationary satellites (Inmarsat) and beamed back to Earth on the GPS L1 frequency (1575.42MHz). The WAAS signals are received by GPS receivers equipped for this task and further processed.

WAAS was developed for the American FAA (Federal Aviation Administration) to provide a high degree of accuracy during landing approaches. The WAAS signal can be accessed for civil use and offers far greater land, sea and air coverage than was previously possible through land-based DGPS systems. WAAS correction signals are valid exclusively in North America.

A.2 Proprietary data interfaces

A.2.1 Introduction

Most manufacturers define their own control commands and data sets. For example, specific information, such as position, speed, height, and status etc. can all be communicated, each manufacturer having developed their own format. The proprietary binary protocol developed by SiRF, which serves as a model for other protocols, is explained in detail, and a few other protocols briefly introduced.

A.2.2 SiRF Binary protocol

GPS receivers fitted with integrated circuits supplied by SiRF in California relay GPS information in two different protocols:

1. the standardised NMEA protocol
2. the proprietary SiRF binary protocol. (SiRF is familiar with more than 15 different proprietary data sets)

The various SiRF data sets are described in Table 21.

SiRF- Data set No.	**Name**	**Description**
2	Measured Navigation Data	Position, speed and time
4	Measured Tracking Data	Signal-to-noise ratio, elevation and azimuth
5	Raw Track Data	Raw distance measurement data
6	SW Version	Receiver software
7	Clock Status	Time measurement status
8	50 BPS Subframe Data	Receiver information (ICD format)
9	Throughput	CPU throughput
11	Command Acknowledgment	Reception confirmation
12	Command NAcknowledgment	Failed inquiry
13	Visible List	Number of visible satellites
14	Almanac Data	Almanac data
15	Ephemeris Data	Ephemeris data
18	OkToSend	CPU On/Off status (trickle power)
19	Navigation Parameters	Reply to the POLL command
255	Development Data	Various internal items of information

Table 21: SiRF output data sets

Detailed description of SiRF data set No. 2

The SiRF proprietary data set No. 2 is presented as follows (Table 22). This particular data set (Measured Navigation Data Out) contains the position and speed calculated by the receiver. It also contains the date and time, and the identification number of the satellites used to perform the position calculation.

SiRF data set No. 2 has the following format:

Name	Bytes	Unit	Remarks
Message ID	1		Always 2
X-Position	4	m	Position calculated by receiver
Y-Position	4	m	
Y-Position	4	m	
X-velocity	2	m/8s	Speed calculated by receiver
Y-velocity	2	m/8s	
Z-velocity	2	m/8s	
Mode 1	1	[Bitmap]	Contains amongst other things algorithmic details for determining position (ex. 2 satellite solution)
DOP	1	1/5	"Dilution of Precision" contains PDOP or HDOP values, depending on the algorithm.
Mode 2	1	[Bitmap]	Contains additional information for differential data
GPS Week	2		Week number since 6th January 1980, on 22nd August 1999 the clock was reset to zero.
GPS TOW	4	s/100	Seconds since the beginning of the previous week
SV's in Fix	1		Number of satellites used to calculate the position
CH1	1		Identification numbers of the satellites used to calculate position
CH2	1		
CH3	1		
CH4	1		
CH5	1		
CH6	1		
CH7	1		
CH8	1		
CH9	1		
CH10	1		
CH11	1		
CH12	1		

Table 22: Structure of proprietary SiRF data set No. 2

A practical example

An example makes clear the structure of data set No. 2:

- Received binary data (Hex. code) with a repetition rate of 1Hz
  A0A2002902FFD6F78CFFBE536E003AC00400030104A00036B039780E30612190E160F04000000000000
  09BBB0B3

- Start sequence:
  A0A2
- Length of the information in bytes
  0029
- Information:
  02FFD6F78CFFBE536E003AC00400030104A00036B039780E30612190E160F04000000000000
- Checksum:
  09BB
- End sequence
  B0B3

The 41 bytes of information are divided up as follows:

Name	**Bytes**	**Scaling**	**Value (Hex)**	**Unit**	**Scaling**	**Value (Decimal)**
Message ID	1		02			2
X-position	4		FFD6F78C	m		-2689140
Y-position	4		FFBE536E	M		-4304018
Z-position	4		003AC004	m		3850244
X-velocity	2	*8	0000	m/s	Vx/8	0
Y-velocity	2	*8	0003	m/s	Vy/8	0.375
Z-velocity	2	*8	0001	m/s	Vz/8	0.125
Mode 1	1		04		Bitmap	4
DOP	1	*5	A		/5	2.0
Mode 2	1		00	Bitmap		0
GPS Week	2		036B			875
GPS TOW	4	*100	039780E3	S	/100	602605.79
SVs in Fix	1		06			6
CH 1	1		12			18
CH 2	1		19			25
CH 3	1		0E			14
CH 4	1		16			22
CH 5	1		0F			15
CH 6	1		04			4
CH 7	1		00			0
CH 8	1		00			0
CH 9	1		00			0
CH 11	1		00			0
CH 11	1		00			0
CH 12	1		00			0

Table 23: Division and meaning of the binary information

A.2.3 Motorola: binary format

GPS receivers and modules supplied by Motorola transmit the GPS information in two different protocols:

1. the standardised NMEA protocol
2. the proprietary Motorola binary format. (Motorola is familiar with up to 35 different proprietary data sets)

A selection of important Motorola data sets is listed in Table 24:

Motorola-Data set No.	Name	Description
@@Aa	Time of Day	Time
@@Ab	GMT Offset	GMT offset
@@Ac	Date	Date
@@Ad	Latitude	Latitude
@@Ae	Longitude	Longitude
@@Af	Height	Height
@@AO	RTCM Port Mode	DGPS mode
@@Ay	1PPS Offset	1PPS offset
@@Az	1PPS Cable Delay	Cable delay
@@Bb	Visible Satellite Status Message	Health of the visible satellites
@@Be	Almanac Data Output	Almanac data output
@@Bo	UTC Offset Status Message	Offset UTC to GPS time
@@Ea	Receiver ID	Identification of the receiver

Table 24: A selection of proprietary Motorola data sets

A.2.4 Trimble proprietary protocol

GPS receivers and modules supplied by Trimble transmit the GPS information in two different protocols:

3. the standardised NMEA protocol
4. the proprietary TSIP binary protocol (Trimble Standard Interface Protocol, Trimble is familiar with as many as 30 different proprietary data sets)

A selection of important Trimble data sets is listed in Table 25.

Trimble Data set No.	Name	Description
0x41	GPS time	GPS time
0x42	Single-precision XYZ position	Single precision XYZ position
0x45	Software version information	Software version
0x46	Health of Receiver	Technical status of receiver
0x47	Signal level for all satellites	Signal strength for all satellites
0x48	GPS system message	GPS system message
0x4A	Single-precision LLA position	Single precision LLA position
0x4D	Oscillator offset	Oscillator frequency offset
0x55	I/O options	I/O options
0x83	Double-precision XYZ	Double precision XYZ position
0x84	Double-precision LLA	Double precision LLA position
0x85	Differential correction status	Differential correction status
0x8F-25	Low power mode	Low power mode
0x8F-27	Low power configuration	Low power configuration

Table 25: A selection of proprietary Trimble data sets

A.2.5 NMEA or proprietary data sets?

GPS modules and appliances generate the standardised NMEA data format and their own proprietary data format. Developers and users of new products are continually confronted with the following issue: which data format is the best and which format is going to be used in new appliances?

NMEA is a standardised data format that is accepted worldwide and that recognises various data sets. The most important information relayed by NMEA interfaces is:

- Geographical position (latitude/longitude/height)
- DOP values
- Elevation and azimuth of the satellites in view
- Course and speed
- Time and date
- Signal-to-noise ratio of the antenna signal

If, for example, a GPS appliance or module is being used with the NMEA data set as part of a system, and that appliance or module has to be replaced, another make can confidently be used. All that the replacement appliance or module needs to function is the RMC NMEA data set.

Proprietary data sets are very flexible. They use data line bandwidth extremely efficiently and, as a result, can generally offer much more information and potential than NMEA data sets. Proprietary interfaces, for example, relay the following additional information over and above NMEA data sets:

- XYZ position and pseudo-ranges
- Raw data
- Ephemeris and almanac data
- Various internal items of information (e.g. software information and receiver ID.)
- UTC offset status message
- Oscillator offset
- Differential correction status

Proprietary data interfaces are therefore manufacturer-specific items, which when used, prevent consumers migrating from one product to another.

RESOURCES ON THE WORLD WIDE WEB

If you would like to . . .

- know where you can learn more about GPS
- know where the GPS system is documented
- become a GPS expert yourself

then you yourself should explore all the Internet links on the subject!

General overviews and further links

Global Positioning System Overview by Peter H. Dana, University of Colorado
http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

Global Positioning System (GPS) Resources by Sam Wormley, Iowa State University
http://www.cnde.iastate.edu/staff/swormley/gps/gps.html

Global Positioning System Data & Information: United States Naval Observatory
http://192.5.41.239/gps_datafiles.html

NMEA-0183 and GPS Information by Peter Bennett,
http://vancouver-webpages.com/peter/

Joe Mehaffey and Jack Yeazel's GPS Information
http://joe.mehaffey.com/

The Global Positioning Systems (GPS) Resource Library
http://www.gpsy.com/gpsinfo/

ABOUT GPS: Satellite Navigation & Positioning (SNAP), University of New South Wales
http://www.gmat.unsw.edu.au/snap/gps/about_gps.htm

GPS SPS Signal Specification, 2nd Edition (June 2, 1995), USCG Navigation Center
http://www.navcen.uscg.gov/pubs/gps/sigspec/default.htm

Differential GPS

Differential GPS (DGPS) by Sam Wormley, Iowa State University
http://www.cnde.iastate.edu/staff/swormley/gps/dgps.html

DGPS corrections over the Internet
http://www.wsrcc.com/wolfgang/gps/dgps-ip.html

Wide Area Differential GPS (WADGPS), Stanford University
http://waas.stanford.edu/

GPS institutes

Institut für Angewandte Geodäsie: GPS-Informations- und Beobachtungssystem
http://gibs.leipzig.ifag.de/cgi-bin/Info_hom.cgi?de

GPS PRIMER :Aerospace Corporation
http://www.aero.org/publications/GPSPRIMER/index.html

U.S. Coast Guard (USCG) Navigation Center
http://www.navcen.uscg.gov/

U.S. Naval Observatory
http://tycho.usno.navy.mil/gps.html

Royal Institute of Navigation, London
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The Institute of Navigation
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University NAVSTAR Consortium (UNAVCO)
http://www.unavco.ucar.edu/

GPS antennae

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http://www.mac-europe.com/

Kyocera Industrial Ceramic Corporation
http://www.kyocera.com/kicc/industrial/products/dielectric.htm

M/A-COM
http://www.macom.com/

EMTAC Technology Corp.
http://www.emtac.com.tw/

Allis Communications Company, Ltd.
http://www.alliscom.com.tw/

GPS newsgroups and specialist journals

Newsgroup: sci.geo.satellite-nav
http://groups.google.com/groups?oi=djq&as_ugroup=sci.geo.satellite-nav

Specialist journal: GPS World (appears monthly)
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