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Essentials of Satellite Navigation

Compendium

Theory and Principles
Systems and Applications Overview

your position is our focus

Compendium

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Foreword

Where on Earth am I?

The answer to this seemingly simple question can sometimes be a matter of life and death. Consider an aviator trying to find a safe destination to land, or the crew of a ship in distress seeking assistance, or a hiker in the mountains disoriented by poor weather conditions. Your position on Earth is of vital importance and can have an immense variety of implications and applications.

These needn't be as dramatic as the circumstances above, but they can be situations that also have a significant impact on our daily lives. How do I find that address that I've been searching for, or when or where should the public transit vehicle trigger the next traffic light? The potential applications and uses of position information are seemingly limitless. Our position on this blue planet has always been vitally important to human beings and today our exact position is something that we can obtain with astonishing ease.

Among the most stunning technological developments in recent years have been the immense advances in the realm of satellite navigation or Global Navigation Satellite Systems (GNSS) technologies. In a matter of a few years, satellite navigation has evolved from the level of science fiction to science fact with a dynamic and rapidly growing industry providing customers around the world with technology devoted to the rapid, reliable and readily available determination of their position.

As global leaders in this fascinating and rapidly changing industry, u-blox AG adds a Swiss accent and our obsession with precision and quality shows through. The men and women of this company are dedicated satellite navigation enthusiasts, and as our motto says, your position is our focus. As part of our commitment to customer service, u-blox AG is pleased to be able to provide you with this compendium to help lead you into the remarkable world of satellite navigation.

The aim of this book is to provide a comprehensive overview of the way in which satellite navigation systems function and the applications to which they can be used. The current level of development as well as changes and innovations will be examined. It is written for users who are interested in the technology as well as specialists involved in satellite navigation applications. The document is structured in such a way that the reader can graduate from simple facts to more complex concepts. The basic theory of satellite navigation will be introduced and supplemented by other important facets. This compendium is intended to additionally serve as an aid in understanding the technology that goes specifically into current satellite navigation receivers, modules and ICs. Important new developments will be dealt with in separate sections. Acquiring an understanding of the various current co-ordinate systems involved in using GNSS equipment can be a difficult task. Therefore, a separate chapter is devoted to introduce cartography.

We hope that this document will be of assistance to you and that you will be as enthusiastic as we are about the technology involved in determining position. It is indeed an immensely fascinating world and industry that answers the question "where on earth am I?"

Author's Preface

In 1990, I was traveling by train from Chur to Brig in the Swiss canton of Valais. In order to pass the time during the journey, I had brought along a few trade journals with me. While thumbing through an American publication, I came across a technical article that described a new positioning and navigation system involving satellites. The new system, known as Global Positioning System or GPS, employed a number of US satellites to determine one's position anywhere in the world to within an accuracy of about 100m[1] .

As an avid sportsman and mountain hiker, I had on many occasions ended up in precarious situations due to a lack of knowledge of the area I was in. Therefore, I was fascinated by the revolutionary prospect of being able to determine my position even in fog or at night by using a GPS receiver.

I began to intensively occupy myself with GPS, arousing a great deal of enthusiasm for this technology among students at my university, which resulted in several research semesters and graduate theses on the subject. With time I felt that I had become a true expert on the subject and wrote technical articles about GPS for various publications.

Why read this book?

The development of the many new and fascinating potential applications of satellite navigation requires an appreciation of the way in which these systems function. If you are familiar with the technical background of the system, it becomes possible to develop and use new positioning and navigation equipment. As well as the possibilities, this book also looks at some of the limitations of the system in order to protect you from unrealistic expectations.

How did this book come about?

In 2000 I decided to reduce the amount of time I spent lecturing at my university in order to gain an overview of the commercial satellite navigation industry. My desire was to work for a company directly involved with satellite navigation and just such a company was u-blox AG, who received me with open arms. u-blox asked me to produce a brochure that they could give to their customers, and this compendium is the result and is a summation of earlier articles and newly compiled chapters.

A heartfelt wish

I wish you every success as you embark on your journey through the wide-ranging world of satellite navigation and trust that you will successfully navigate your way through this fascinating technical field. Enjoy your read!

Jean-Marie Zogg

October 2001

July 2006

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[1] That was in 1990, positional data is now accurate to within 5 to 10m!

Contents

Introduction

Satellite Navigation is a method employing a Global Navigation Satellite System (GNSS) to accurately determine position and time anywhere on the Earth. Satellite Navigation receivers are currently used by both private individuals and businesses for positioning, locating, navigating, surveying, and determining the exact time in an ever-growing list of personal, leisure and commercial applications.

Using a GNSS system the following values can accurately be determined anywhere on the globe (Figure 1):

1. Exact position (longitude, latitude and altitude co-ordinates) accurate to within 20 m to approx.1 mm.
2. Exact time (Universal Time Coordinated, UTC) accurate to within 60ns to approx. 5ns.

Speed and direction of travel (course) can be derived from these values, which are obtained from satellites orbiting the Earth.

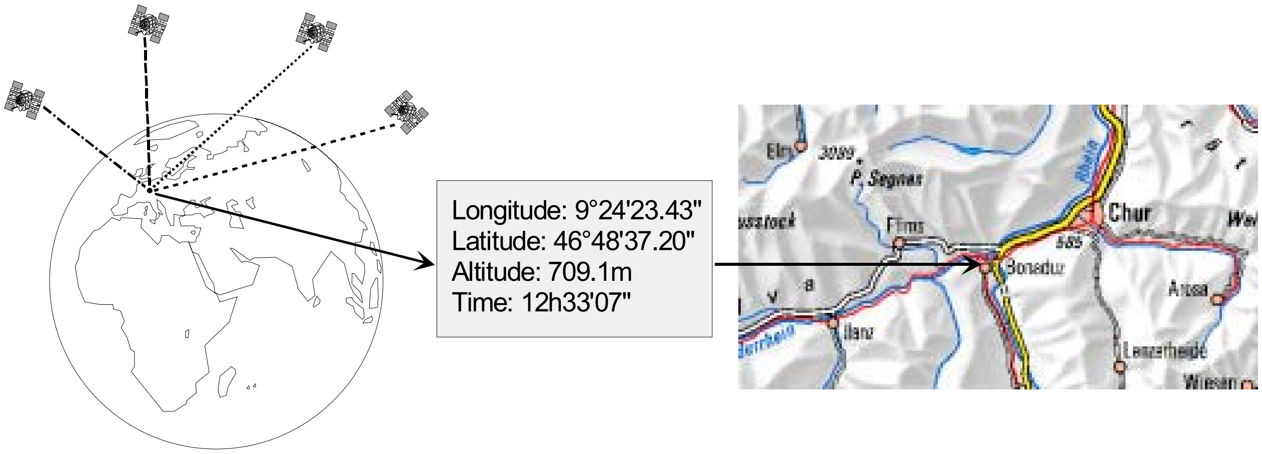

Figure 1: The basic function of satellite navigation

As of 2007, the **G**lobal **P**ositioning **S**ystem (GPS) developed and operated by the United States Department of Defense (DoD) was the only fully operational GNSS system. The rapidly developing Satellite Navigation industry has sprung up around the GPS system, and for this reason the terms GPS and Satellite Navigation are sometimes used interchangeably. This document will place an emphasis on GPS, although other emerging GNSS systems will be introduced and discussed.

GPS (the full name of the system is: **NAV**igation **S**ystem with **T**iming **A**nd **R**anging **G**lobal **P**ositioning **S**ystem, NAVSTAR-GPS) is intended for both civilian and military use. The civilian signal SPS (Standard Positioning Service) can be used freely by the general public, while the military signal PPS (Precise Positioning Service) is available only to authorized government agencies. The first satellite was placed in orbit on February 22, 1978, and it is planned to have up to 32 operational satellites orbiting the Earth at an altitude of 20,180 km on 6 different orbital planes. The 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 onboard.

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, all-weather 3-dimensional positioning capability with a high degree of accuracy.
3. It had to offer potential for civilian use.

Within the next five or six years there will likely be 3 fully independent GNSS systems available. The United States will continue to provide GPS and Russia and the European Union should respectively bring their GLONASS and GALILEO systems into full operation. All of these systems will undergo modernization and improvements, which should improve their reliability and make new potential services and applications available[2].

This compendium will examine the essential principles of Satellite Navigation and move beyond these into specific applications and technologies. GPS will receive particular focus because of its importance as forerunner and industry standard, and important developments such as Differential-GPS (DGPS), Assisted-GPS (AGPS) and Device Interfaces will be treated in separate sections. This is all with the goal of providing the reader with a solid foundation and understanding of this fascinating and increasingly important field.

Figure 2: Launch of GPS Satellite

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[2] Among these will be important advances for aviation, wherein approaches and landings using satellite navigation should become possible.

1 Satellite Navigation Made Simple

Do you want to . . .

- understand, how the distance of lightning can be simply determined?
- understand, how Satellite Navigation essentially functions?
- know, how many atomic clocks are onboard a GPS satellite?
- know, how to determine a position on a plane?
- understand, why Satellite Navigation requires four satellites to determine a position?

*Then you should read **this chapter**!*

1.1 The principle of measuring signal transit time

At some time or other during a thunderstorm you have almost certainly attempted to work out how far away you are from a bolt of lightning. The distance can be established quite easily (Figure 3): 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 referred to as the signal travel time. In this case the signal is sound waves traveling through the air.

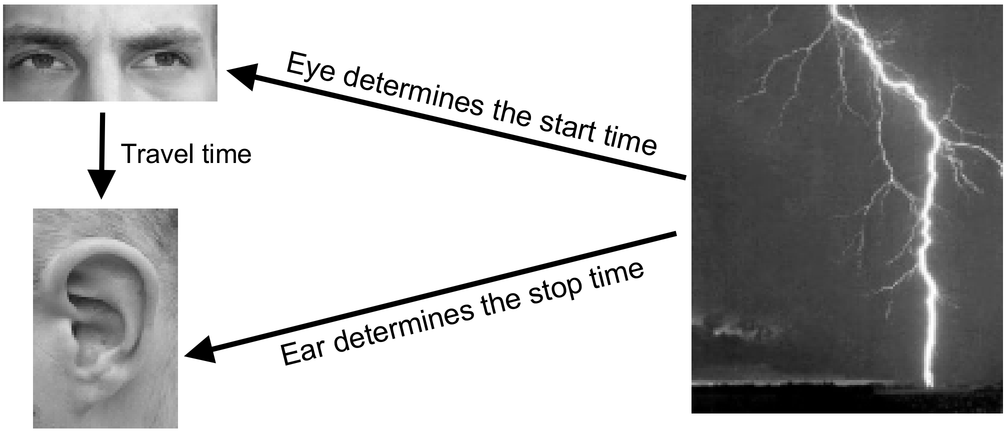


Figure 3: Determining the distance of a lightning flash

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

Satellite Navigation functions by the same principle. One calculates position by establishing the distance relative to reference satellites with a known position. In this case the distance is calculated from the travel time of radio waves transmitted from the satellites.

1.1.1 Basic Principles of Satellite Navigation

Satellite Navigation Systems all use the same basic principles to determine coordinates:

- Satellites with a known position transmit a regular time signal.
- Based on the measured travel time of the radio waves (electromagnetic signals travel through space at the speed of light c = 300’000km/s) the position of the receiver is calculated.

We can see the principle more clearly using a simple model. Imagine that we are in a car and need to determine our position on a long and straight street. At the end of the street is a radio transmitter sending a time signal pulse every second. Onboard the car we are carrying a clock, which is synchronized to the clock at the transmitter. By measuring the elapsed travel time from the transmitter to the car we can calculate our position on the street (Figure 4).

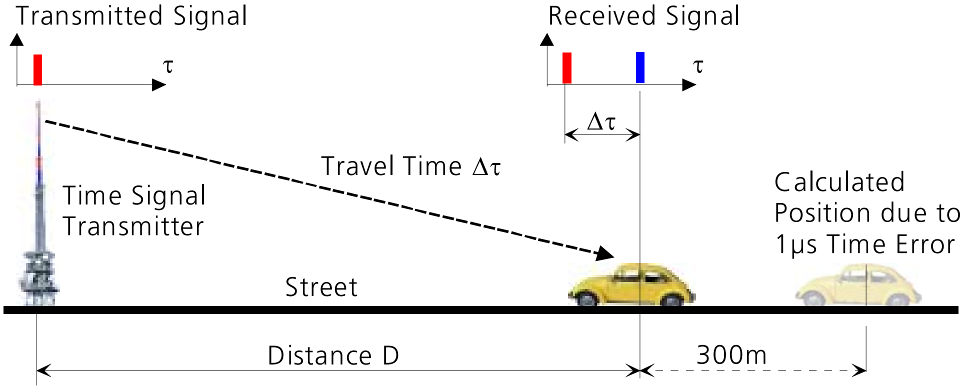


Figure 4: In the simplest case Distance is determined by measuring the Travel Time

The distance D is calculated by multiplying the travel time $\Delta\tau$ by the velocity of light c.

$D = \Delta\tau \bullet c$

Because the time of the clock onboard our car may not be exactly synchronized with the clock at the transmitter, there can be a discrepancy between the calculated and actual distance traveled. In navigation this incorrect distance is referred to as pseudorange. In our example a time error of one microsecond (1µs) generates a pseudorange of 300m.

We could solve this problem by outfitting our car with an exact atomic clock, but this would probably exceed our budget. Another solution involves using a second synchronized time signal transmitter, for which the separation (A) to the first transmitter is known. By measuring both travel times it is possible to exactly establish the distance (D) despite having an imprecise onboard clock.

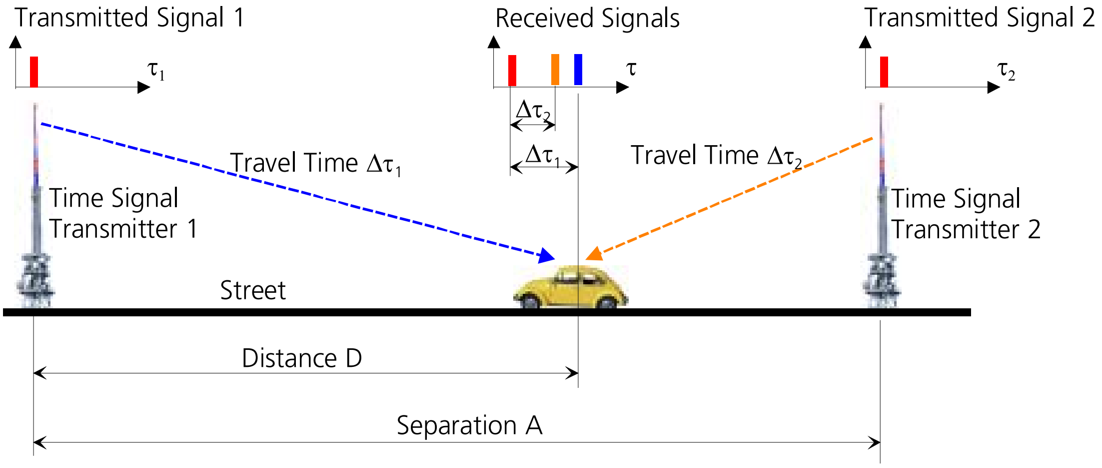


Figure 5: With two transmitters it is possible to calculate the exact position despite Time Errors.

$$D = \frac{(\Delta\tau_1 - \Delta\tau_2)\bullet c + A}{2}$$

As we have seen, in order to exactly calculate the position and time along a line (by definition a line expands in one dimension) we require two time signal transmitters. From this we can draw the following conclusion: When an unsynchronized onboard clock is employed in calculating position, it is necessary that the number of time signal transmitters exceed the number of unknown dimensions by a value of one.

For Example:

- On a plane (Expansion in two dimensions) we need three time signal transmitters.
- In three-dimensional space we need four time signal transmitters.

Satellite Navigation Systems use satellites as time signal transmitters. Contact to at least four satellites (Figure 6) is necessary in order to determine the three desired coordinates (Longitude, Latitude, Altitude) as well as the exact time. We explain this in more detail in following sections.

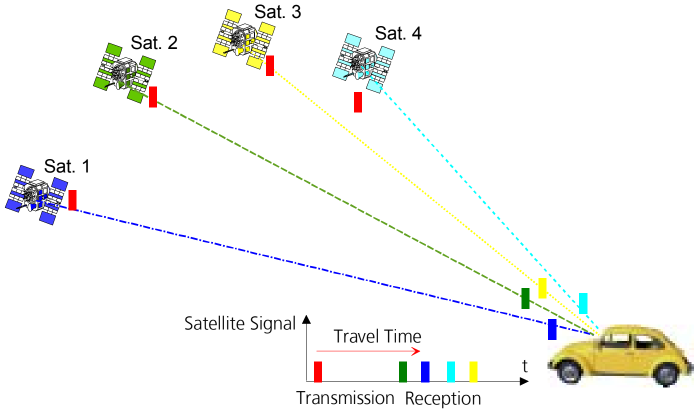
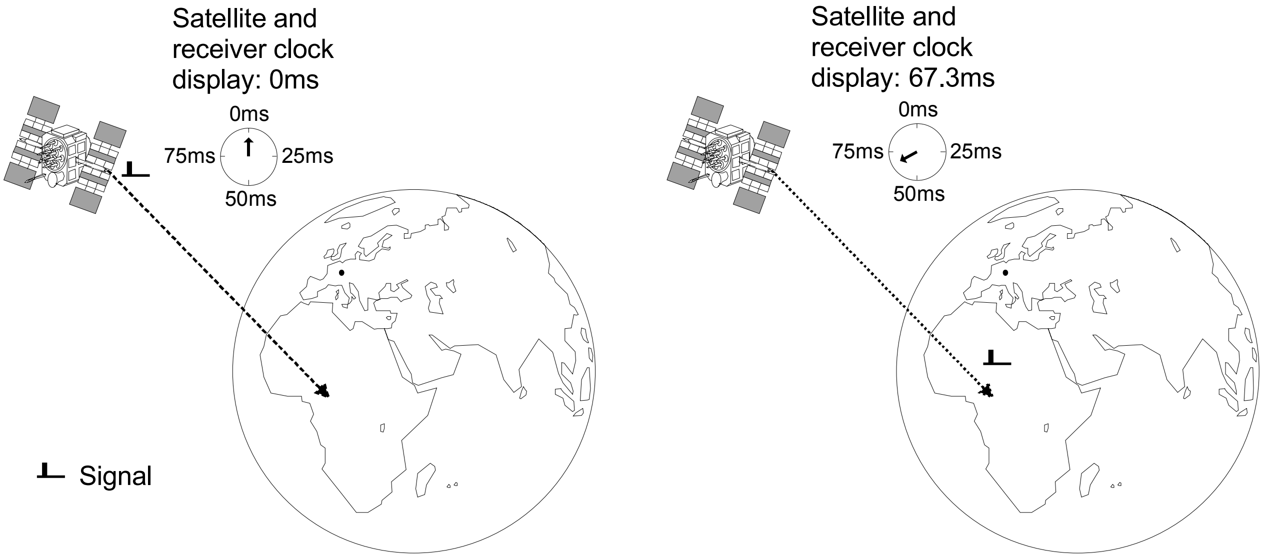


Figure 6: Four satellites are needed to determine Longitude, Latitude, Altitude and Time

1.1.2 Signal travel time

Satellite Navigation Systems employ satellites orbiting high above the Earth and distributed in such a way that from any point on the ground there is line of sight contact to at least 4 satellites.

Each one of these satellites is equipped with onboard atomic clocks. Atomic clocks are the most precise time measurement 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 synchronized from various control points on Earth. GNSS satellites transmit their exact position and onboard clock time to Earth. 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 directly below the satellite. The signals require a further 3.33 µs for each addtional kilometer of travel. To establish position, all that is required is a receiver and an accurate clock. By comparing the arrival time of the satellite signal with the onboard clock time the moment the signal was transmitted, it is possible to determine the signal travel time (Figure 7).



Signal transmission (start time)

Signal reception (stop time)

Figure 7: Determining the signal travel time

As with the example of the car, the distance D to the satellite can be determined from the known signal travel time Δτ:

$$\text{distance} = \text{travel time} \bullet \text{speed of light}:$$
$$D = \Delta\tau \bullet c$$

1.1.3 Determining position

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 onboard clock times and positions. By using the signal travel time to both satellites you can draw two circles with the radii D_1 and D_2 around the satellites. Each radius corresponds to the distance calculated to the satellite. All possible positions relative to the satellites are located on these circles. 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 8), therefore, two satellites are sufficient to determine a position on the X/Y plane.

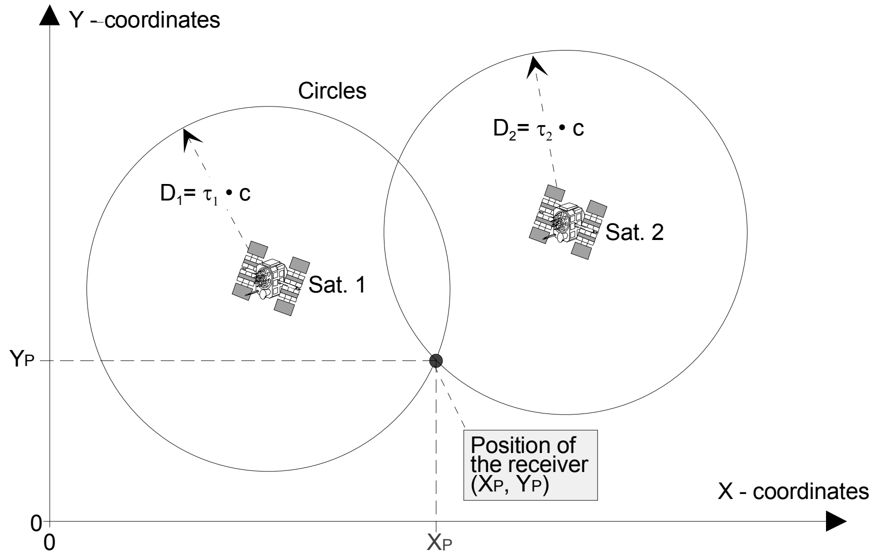


Figure 8: The position of the receiver at the intersection of the two circles

In the real world, 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 is the point where all three of the spheres intersect (Figure 9).

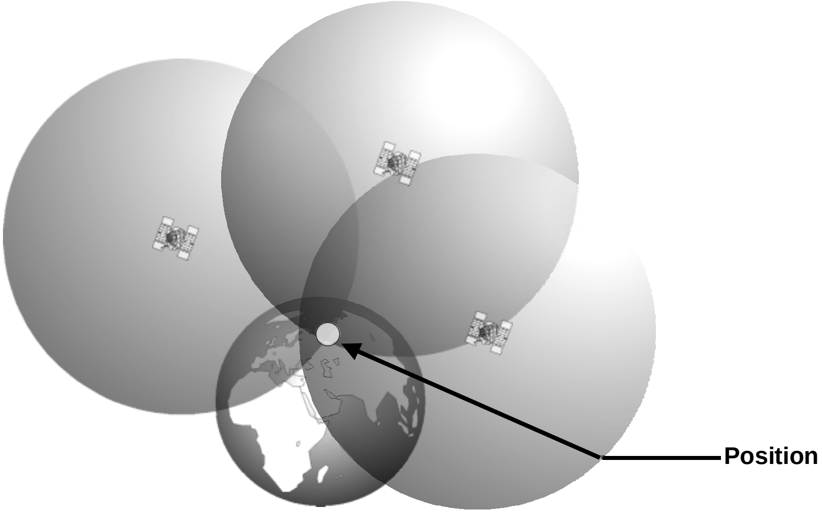


Figure 9: The position is determined at the point where all three spheres intersect

1.1.4 The effect and correction of time error

The conclusions in the previous section are only valid, if the clock at the receiver and the atomic clocks onboard the satellites are synchronized, i.e. the signal travel time can be precisely determined. If the measured travel time between the satellites and an earthbound navigational receiver is incorrect by just 1µs, this produces a position error or pseudorange of 300m. As the clocks onboard all the GNSS satellites are synchronized, the signal travel time in the case of all three measurements is inaccurate by the same amount. Mathematics can help us in this situation.

We are reminded when performing mathematical calculations that if N variables are unknown, we need N independent equations to identify them. If the time measurement is accompanied by a constant unknown error (Δt), in 3-Dimensional space we will have four unknown variables:

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

These four variables require four equations, which can be derived from four separate satellites.

Satellite Navigation systems are deliberately constructed in such a way that from any point on Earth, at least 4 satellites are "visible" (Figure 10). Thus despite inaccuracy on the part of the receiver clock and resulting time errors, a position can be calculated to within an accuracy of approx. 5 – 10 m.

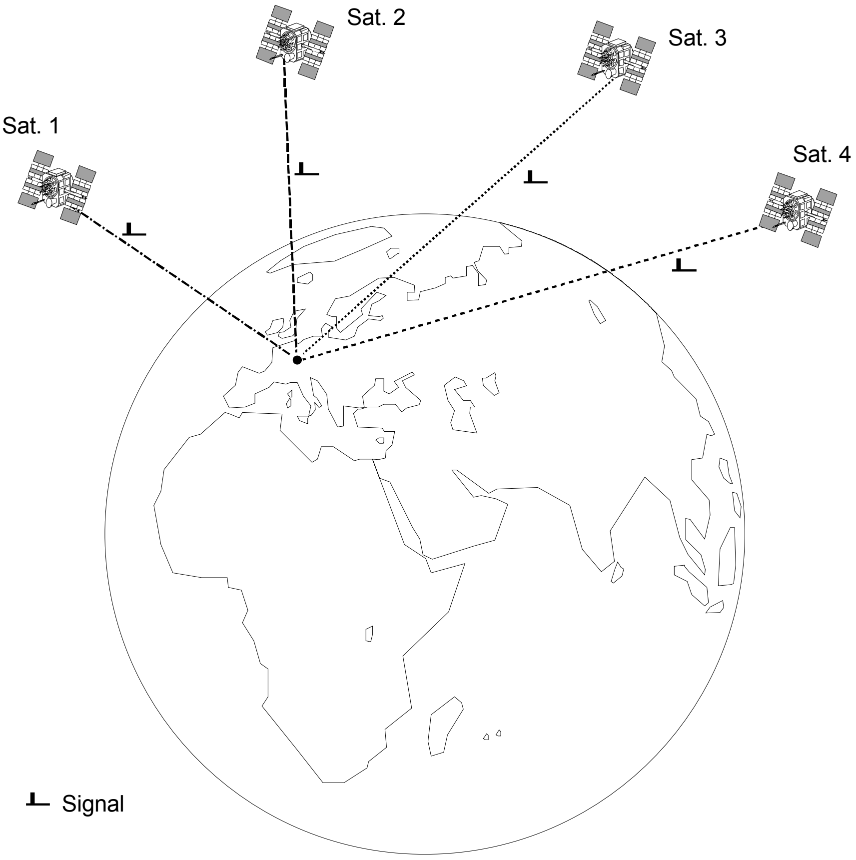


Figure 10: Four satellites are required to determine a position in 3-D space.

2 GNSS Technology: The GPS example

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 transmitted to Earth
- understand how a satellite signal is generated
- understand how Satellite Navigation signal travel time is determined
- understand what correlation means
- understand why a minimum period of time is required for the GPS system to come online
- know what frames and subframes are

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

2.1 Description of the entire system

In the following sections we will explore the different segments of GNSS technology by specifically looking at the GPS system.

The GPS system is comprised of three functional segments (Figure 11):

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

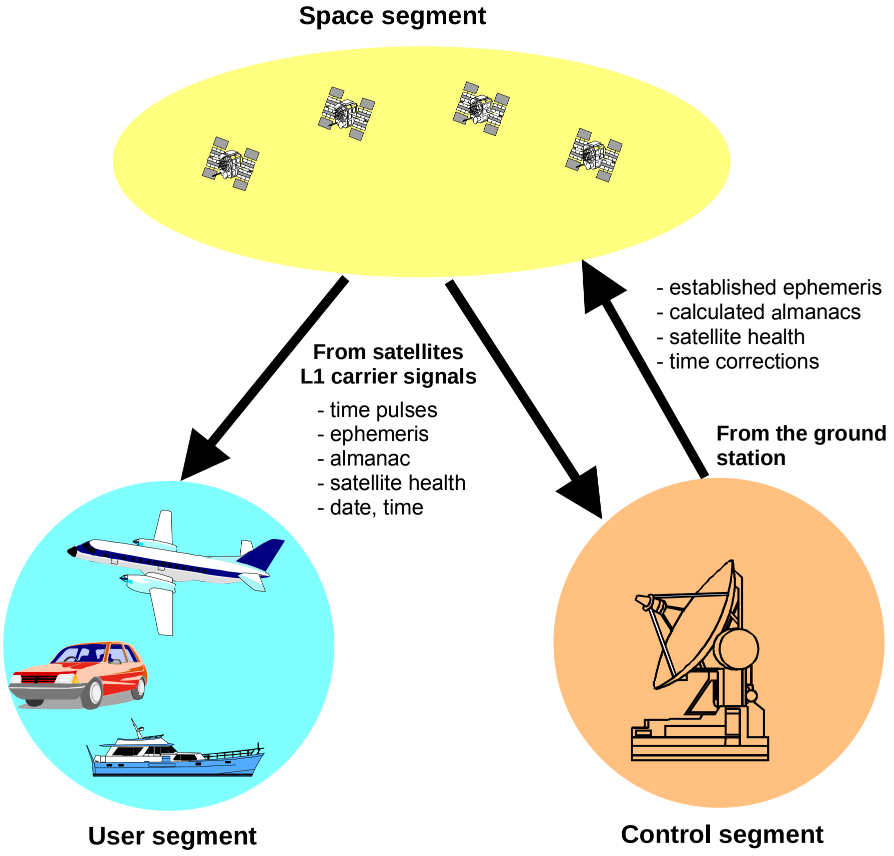


Figure 11: The three GNSS segments

As can be seen in Figure 11 there is unidirectional communication between the space segment and the user segment. The ground control stations have bidirectional communication with the satellites.

2.2 Space segment

2.2.1 Satellite distribution and movement

The space segment of the GPS system consists of up to 32 operational satellites (Figure 12) 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 above the earth's surface (Figure 13) after approx. 24 hours (23 hours 56 minutes to be precise).

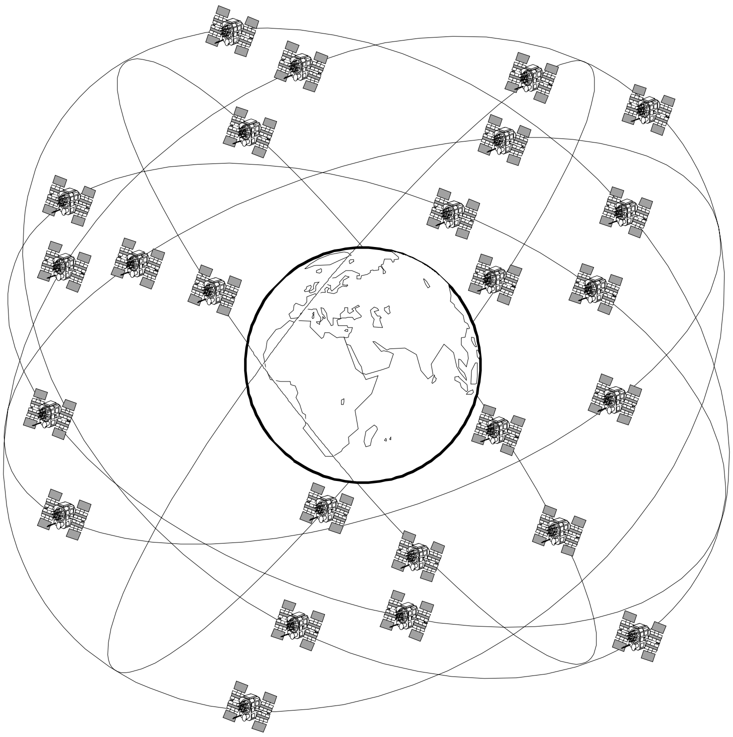


Figure 12: GPS satellites orbit the Earth on 6 orbital planes

Satellite signals can be received anywhere within a satellite's effective range. Figure 13 shows the effective range (shaded area) of a satellite located directly above the equator/zero meridian intersection.

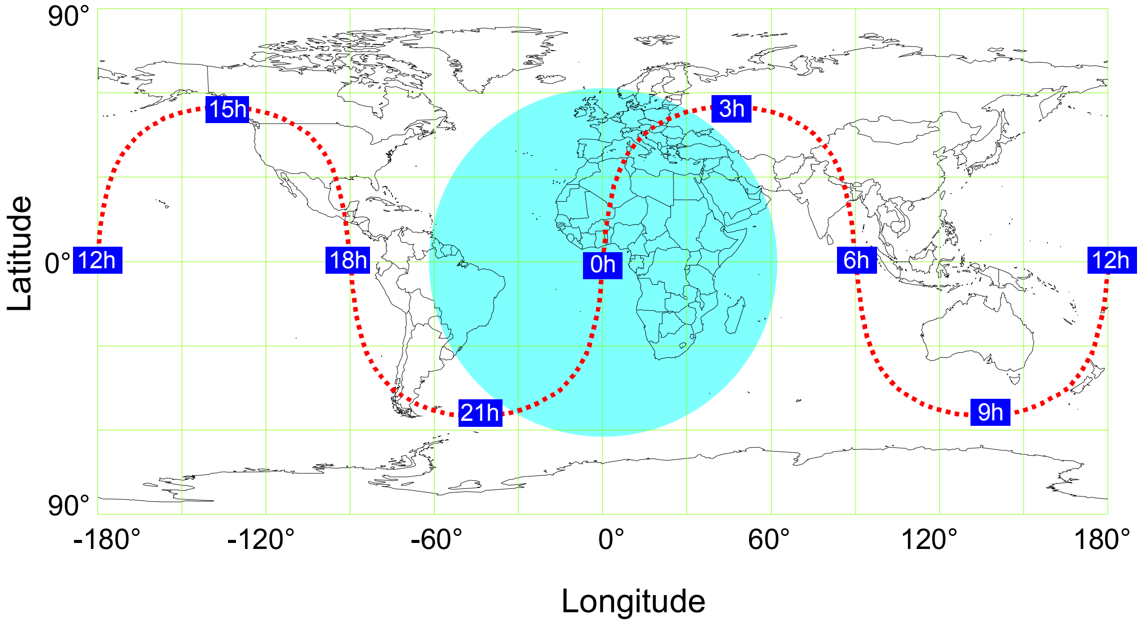


Figure 13: 24 hour tracking of a GPS satellite with its effective range

The distribution of the satellites at a specific time can be seen in Figure 14. It is due to this ingenious pattern of distribution and to the high orbital altitudes that communication with at least 4 satellites is ensured at all times anywhere in the world.

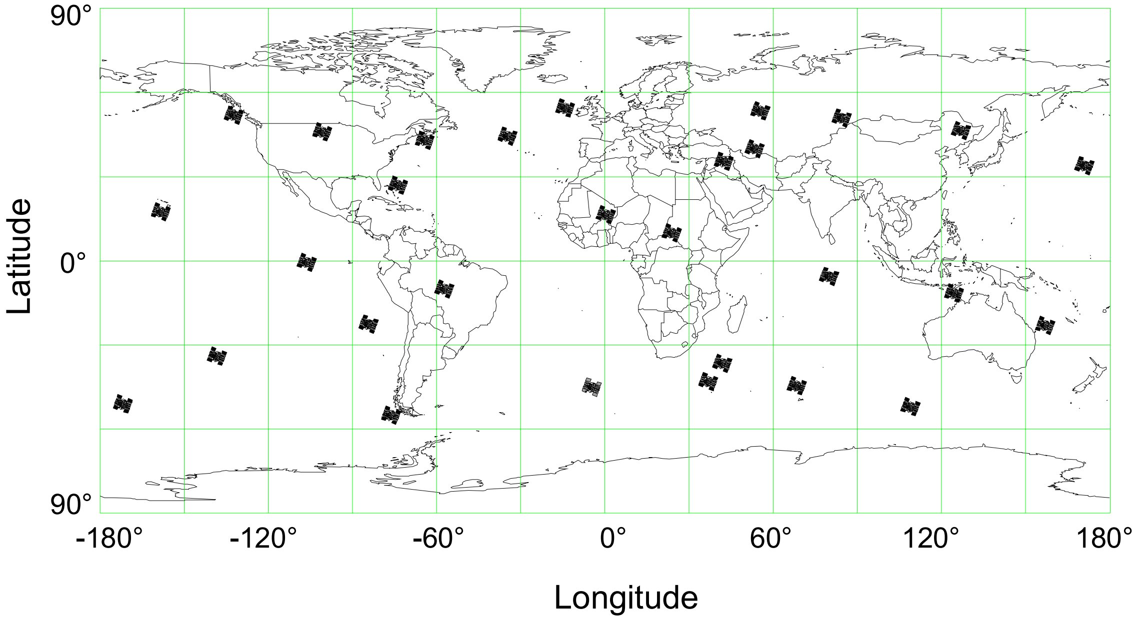


Figure 14: Position of the GPS satellites at 12:00 hrs UTC on 14th April 2001

2.2.2 The GPS satellites

2.2.2.1 Satellite Construction

All of the satellites use onboard atomic clocks to maintain synchronized signals, which are transmitted over the same frequency (1575.42 MHz). The minimum signal strength received on Earth is approx. -158dBW to -160dBW [i]. According to the specifications, the maximum strength is approx. -153dBW.

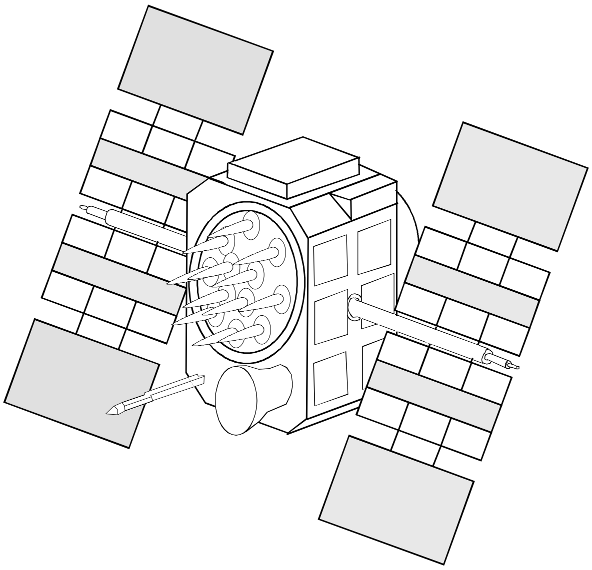


Figure 15: A GPS satellite

2.2.2.2 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. According to the specifications, 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 polarization 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

According to the specifications, the power of the received GPS signal in open sky is at least -160dBW (-130dBm). The maximum of the spectral power density of the received signal is given as -190 dBm/Hz (Figure 16). The spectral power density of the thermal background noise is about –174 dBm/Hz (at a temperature of 290 K). Thus the maximum received signal power is approximately 16 dB below the thermal background noise level.

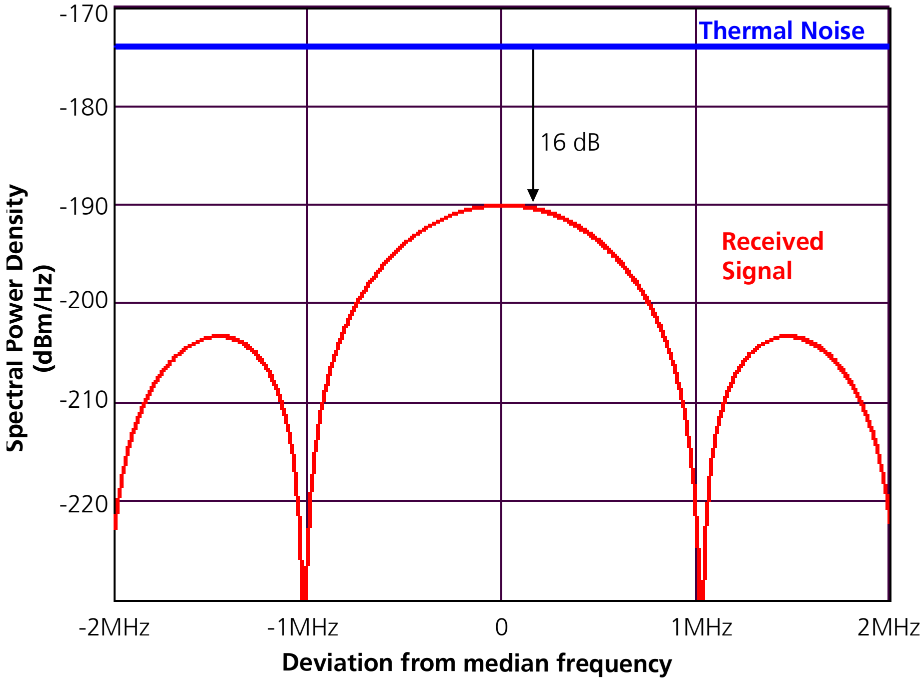


Figure 16: Spectral Power Density of received signal and thermal noise

2.2.2.3 Satellite signals

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

- Satellite time and synchronization 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 the operating status (health) of the satellite

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 GPS satellite transmits a unique signature assigned to it. This signature consists of a Pseudo Random Noise (PRN) Code of 1023 zeros and ones, broadcast with a duration of 1ms and continually repeated (Figure 17).

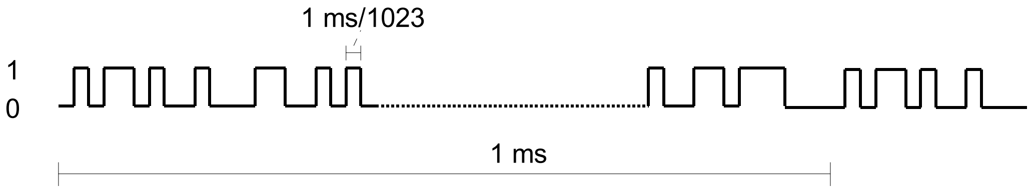


Figure 17: Pseudo Random Noise

The signature code serves the following two purposes for the receiver:

- Identification: the unique signature pattern identifies the satellite from which the signal originated.
- Signal travel time measurement

2.2.3 Generating the satellite signal

2.2.3.1 Simplified block diagram

Onboard each of the satellites are four highly accurate atomic clocks. The resonance frequency of one of these clocks generates the following time pulses and frequencies required for operations (Figs. 13 and 14):

- The 50 Hz data pulse
- The C/A (Coarse/Acquisition) code (a PRN-Code broadcast at 1.023 MHz), which modulates the data using an exclusive-or operation (EXOR)[3] spreading the data over a 2MHz 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 Binary-Phase-Shift-Keying (BPSK)[4]. With every change in the modulated data there is a 180° change in the L1 carrier phase.

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[3] A logical operation on two operands that results in a logical value of *true* if and only if exactly one of the operands has a value of *true*.

[4] A method of modulating a carrier wave so that data is translated into 90° phase shifts of the carrier.

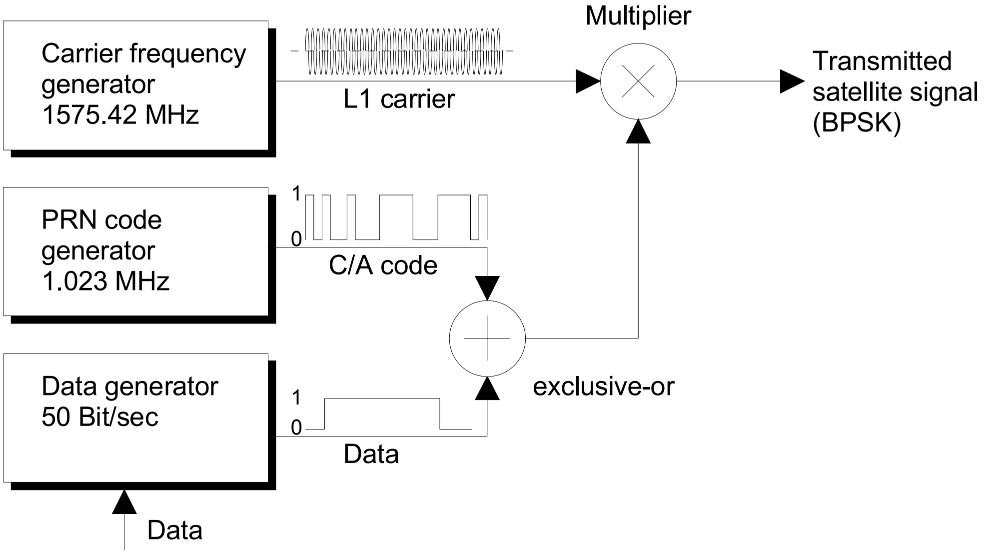

Figure 18: Simplified satellite block diagram

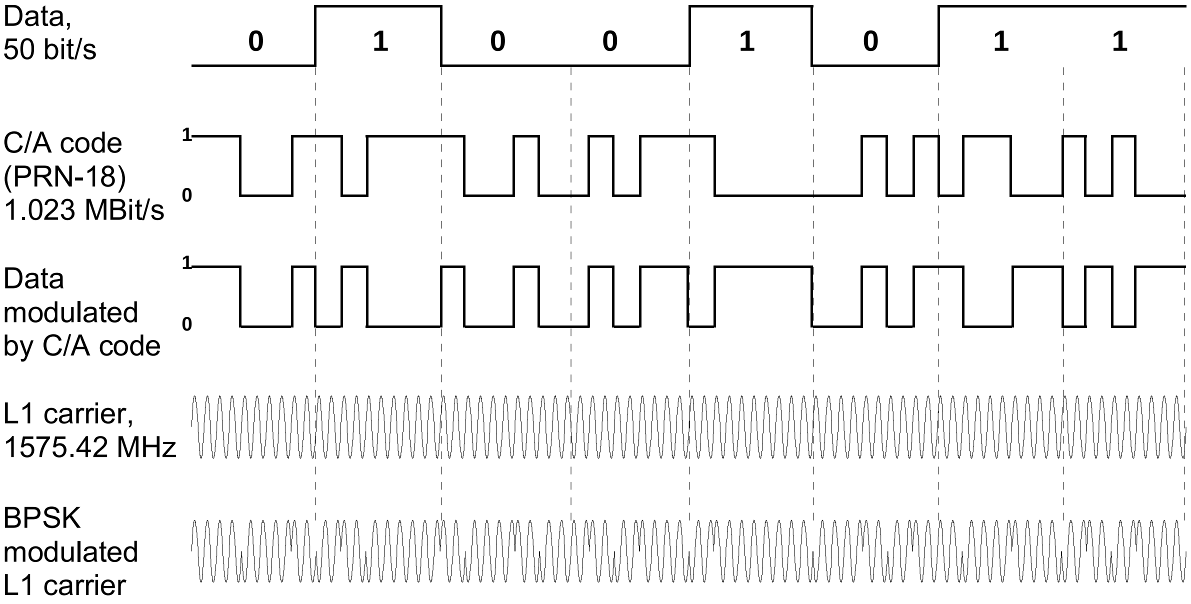

Figure 19: Data structure of a GPS signal

2.2.3.2 Detailed block diagram

Satellite navigation signals are generated using a process known as DSSS (Direct Sequence Spread Spectrum) modulation [iii]. This is a procedure in which a nominal or baseband (not to be confused with the baseband chip in the receiver) frequency is deliberately spread out over a wider bandwidth through superimposing a higher frequency signal. The principle of spread-spectrum modulation was first devised in the 1940s in the United States, by screen actress Hedy Lamarr and pianist George Anthell [iv]. This process allows for secure radio links even in difficult environments.

GPS satellites are each equipped with four extremely stable atomic clocks (possessing a stability of greater than $20 \cdot 10^{-12}$ [v]). The nominal or baseband frequency of 10.23MHz is produced from the resonant frequency of one of these onboard clocks. In turn, the carrier frequency, data pulse frequency and C/A (coarse/acquisition) code are all derived from this frequency (Figure 20). Since all the GPS satellites transmit on 1575.42 MHz, a process known as a CDMA (Code Division Multiple Access) Multiplex[5] is used.

The C/A code plays an important role in the multiplexing and modulation. It is a constantly repeated sequence of 1023 bits known as a pseudo random noise (PRN) code. This code is unique to each satellite and serves as its identifying signature. The C/A code is generated using a feedback shift register[6]. The generator has a frequency of 1.023 MHz and a period of 1023 chips[7], which corresponds to 1ms. The C/A code is a Gold Code[8], which has advantageous correlation properties. This has important implications later on in the navigation process in the calculation of position.

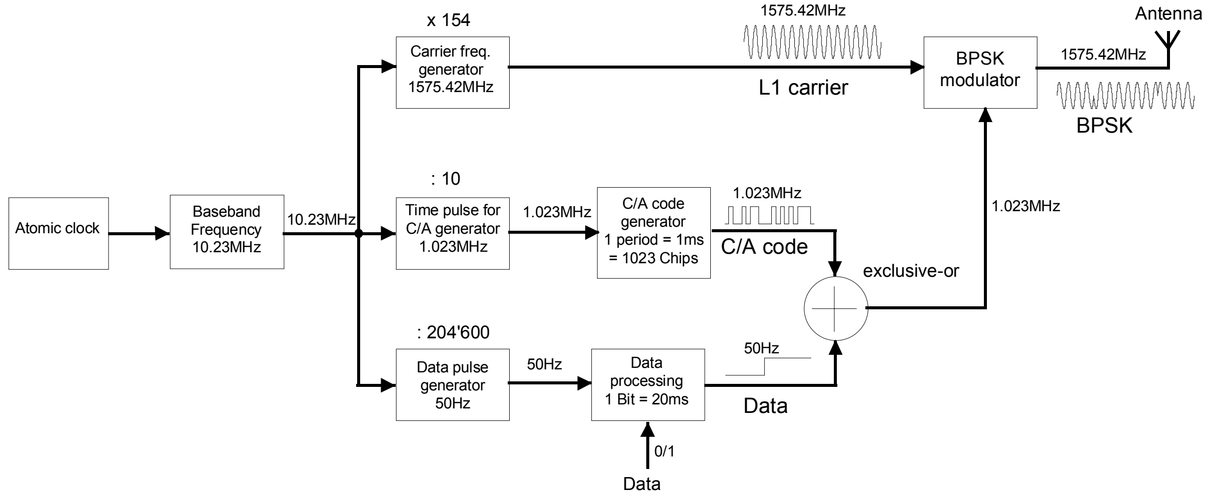

Figure 20: Detailed block diagram of a GPS satellite

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[5] A form of multiplexing that divides up a radio channel by using different pseudo-random code sequences for each user. CDMA is a form of "spread-spectrum" signalling, since the modulated code signal has a much higher bandwidth than the data being communicated.

[6] A shift register whose input bit is a linear function of its previous state.

[7] The transition time for individual bits in the pseudo-random sequence.

[8] A Gold code is a set of binary sequences. Pick two m-sequences of the same length n, such that their cross-correlation takes just three values. The set of the n exclusive-ors of the two sequences in their various phases (i.e. translated into all relative positions), together with the two n-sequences themselves, is a set of Gold codes. The exclusive or of two Gold codes is another Gold code in some phase.

2.3 Control segment

The GPS control segment (Operational Control System OCS) consists of a Master Control Station located in the state of Colorado, five monitor stations (each equipped with atomic clocks and distributed around the globe in the vicinity of the equator), and three ground control stations transmitting 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 behavior
- Synchronizing onboard satellite time
- Relaying precise orbital data received from satellites
- 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. Until May 2000 the U.S.DoD (the GPS operators) intentionally degraded system accuracy for political and strategic reasons. This can be resumed, if deemed necessary, either on a global or regional basis.

2.4 User segment

The radio signals transmitted by the GPS satellites take approx. 67 milliseconds to reach a receiver on Earth. As the signals travel at a constant speed (the speed of light c), their travel time determines the exact distance between the satellites and the user.

Four different signals are generated in the receiver, each having the same structure as the signals received from the 4 satellites. By synchronizing the signals generated in the receiver with those from the satellites, the signal time shifts Δt of the four satellites are measured as a time mark (Figure 21). The measured time shifts Δt of all 4 satellite signals are then used to determine the exact signal travel time. These time shifts are called pseudoranges.

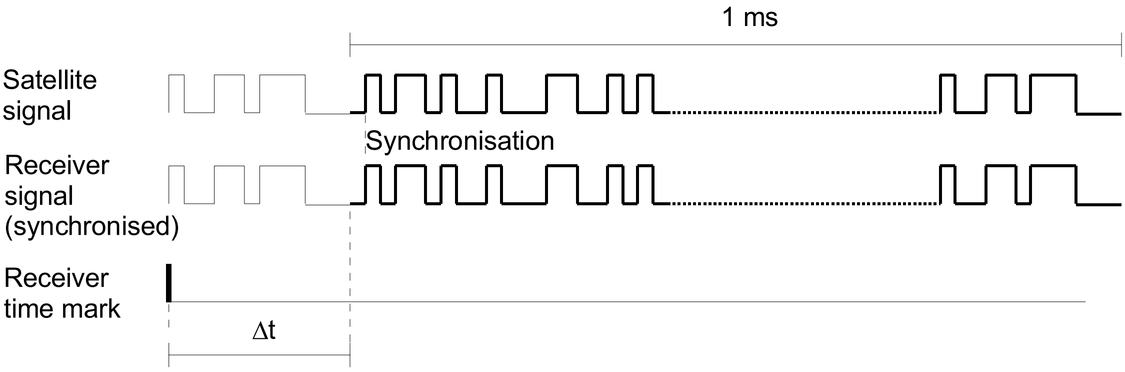

Figure 21: Measuring signal travel time

In order to determine the position of a user, radio communication with four different satellites is required. The distance to the satellites is determined by the travel time of the signals. The receiver then calculates the user's latitude φ, longitude λ, altitude h and time t from the pseudoranges 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 the GPS satellites transmit on the same frequency, but with a different C/A code. Identification of the satellites and signal recovery take place by means of a correlation. As the receiver is able to recognize all C/A codes currently in use, by systematically shifting and comparing every known code with all incoming satellite signals, a complete match will eventually occur (that is to say the correlation factor CF is one), and a correlation point will be attained (Figure 22). The correlation point is used to measure the actual signal travel time and to identify the satellite.

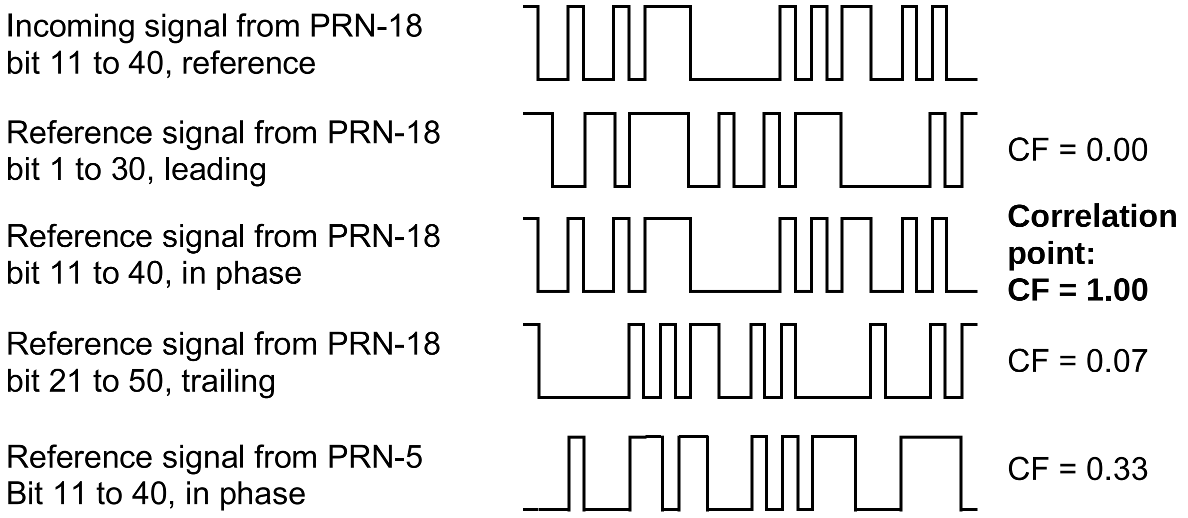

Figure 22: Demonstration of the correction process across 30 bits

The quality of the correlation is expressed here as a CF (correlation factor). The value range of the CF lies between minus one and plus one and is only plus one when the 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.

As a result of the Doppler Effect (satellites and receivers are in relative motion to one another) the transmitted signals can be shifted by up to ±6000 Hz at the point of reception. The determination of the signal travel time and data recovery therefore requires not only correlation with all possible codes at all possible phase shifts, but also identification of the correct phase carrier frequency. Through systematic shifting and comparison of all the codes (Figure 22) and the carrier frequency with the incoming satellite signals there comes a point that produces a complete agreement (i.e. the correlation factor is one) (Figure 23). A search position in the carrier frequency level is known as a bin.

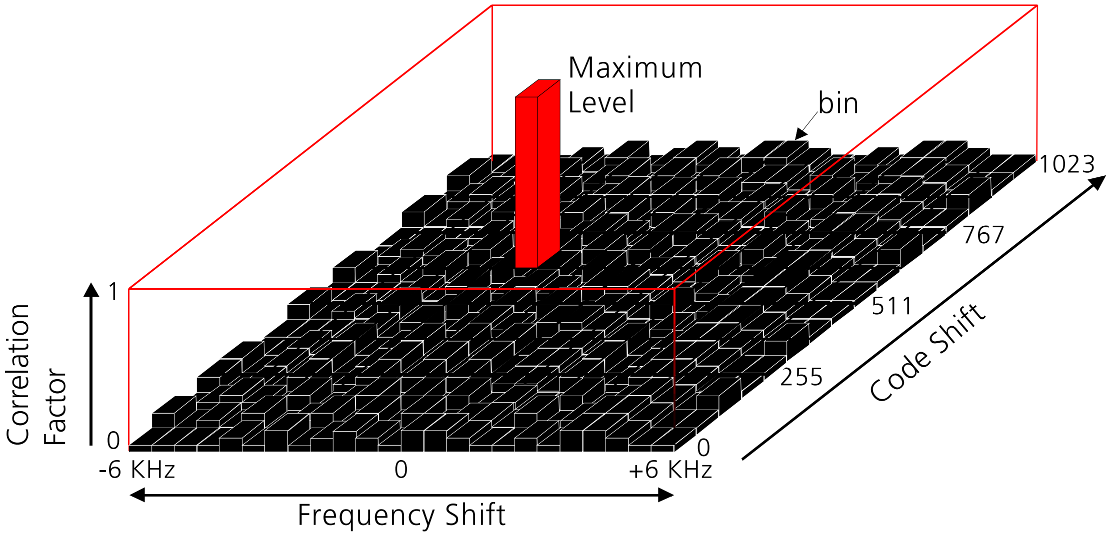

Figure 23: Search for the maximum correlation in the code and carrier frequency domains

The spectral power density of the received GPS signal lays at approximately 16 dB below the spectral power density of the thermal or background noise (see Figure 16). The demodulation and despreading of the received GPS signal causes a system gain G_G of:

$$G_G = \frac{\text{Modulation rate of C/A-Code}}{\text{Data rate of information signal}} = \frac{1023\,\text{bps}}{50\,\text{bps}} = 20{,}500 = 43\,\text{dB}$$

After despreading, the power density of the usable signal is greater than that of the thermal or background signal noise (Figure 24).

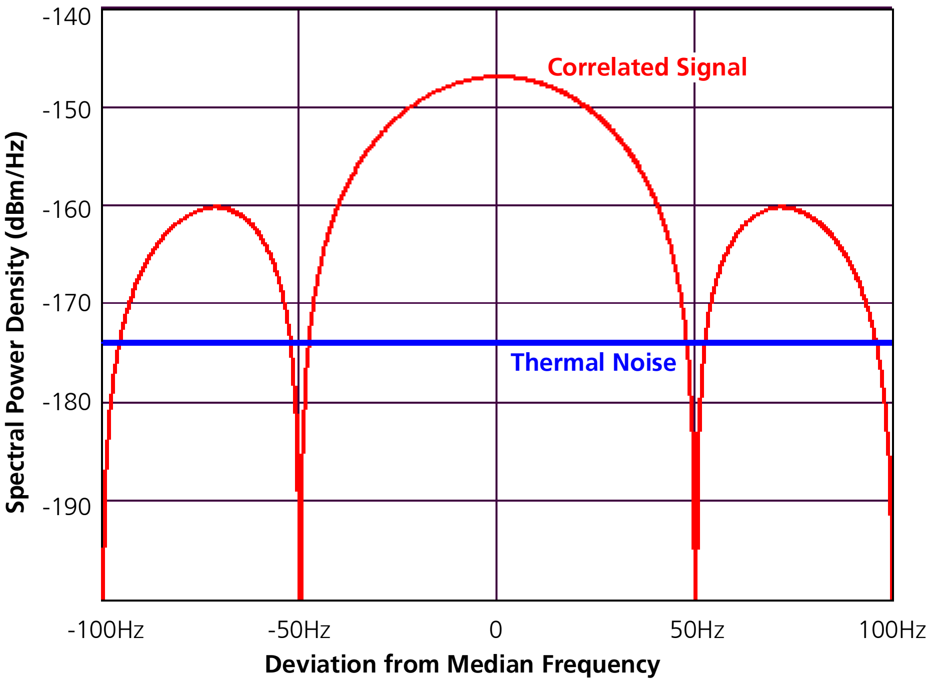

Figure 24: Spectral Power Density of the correlated signal and Thermal Signal Noise

The sensitivity of a GPS Receiver can be improved through increasing the correlation time (Dwell Time). The longer a correlator remains at a specific point in the Code Frequency Level, the lower will be the required GPS signal strength at the antenna. When the correlation time is increased by a factor of k, there will be an improvement G_R in the difference between the Signal and the Thermal Background Noise of:

$G_R = \log_{10}(k)$

Doubling the Dwell Time increases the difference between the Signal and the Thermal Background Noise (the sensitivity of the receiver) by 3dB. In practice it is not a problem to increase the correlation time up to 20 ms. If the value of the transmitted data is known, then this time can be increased even more.

2.5 The GPS Message

2.5.1 Introduction

The GPS 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 travel 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. Transmission time for the entire almanac is therefore 12.5 minutes. Unless equipped with GPS enhancement (see chapter 6) a GPS receiver must have collected the complete almanac at least once in order to calculate its initial position.

2.5.2 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 a diagram in Figure 25.

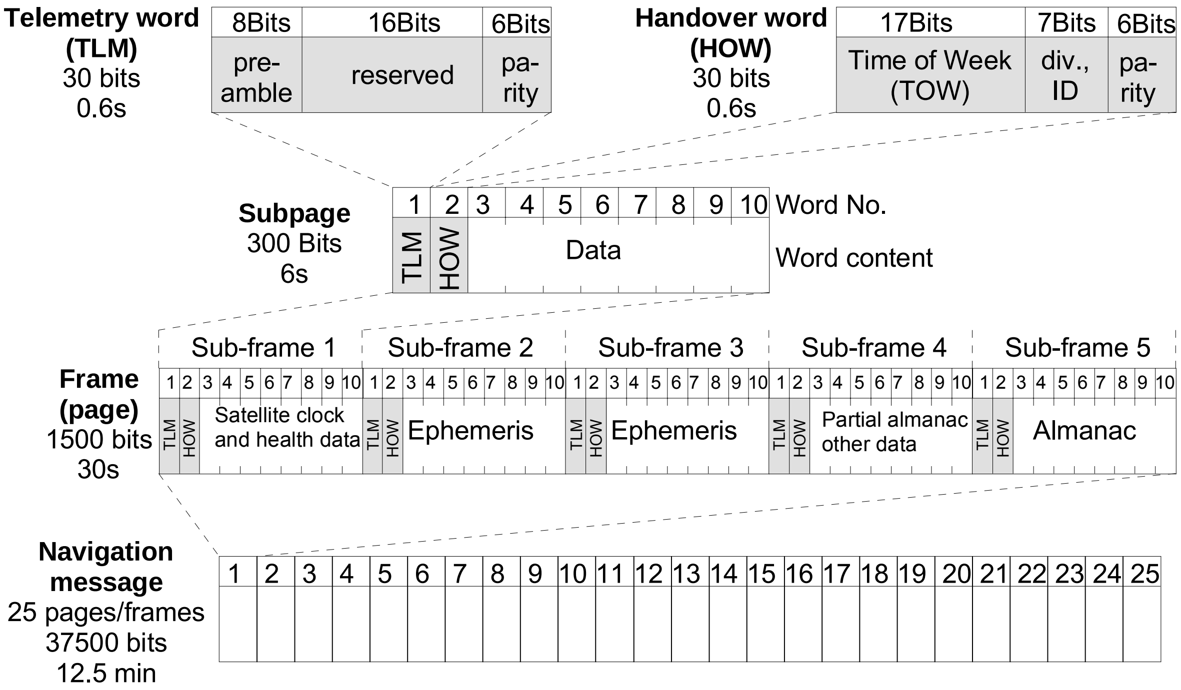

Figure 25: Structure of the entire navigation message

2.5.3 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 onboard clock time, as well as information on satellite health and an estimate 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. This event is called a "week rollover".
- 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 (leap seconds or UTC offset) 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.

2.5.4 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 synchronization with the P code. Bit Nos. 20 to 22 are used in the handover word to identify the subframe just transmitted.

2.5.5 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 only difference in the case of subframes 4 and 5 is how the information transmitted is organized.

- 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.

2.5.6 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

The orbit of a satellite follows an ellipse. For an explanation of the terms used in Table 2, see Figure 26.

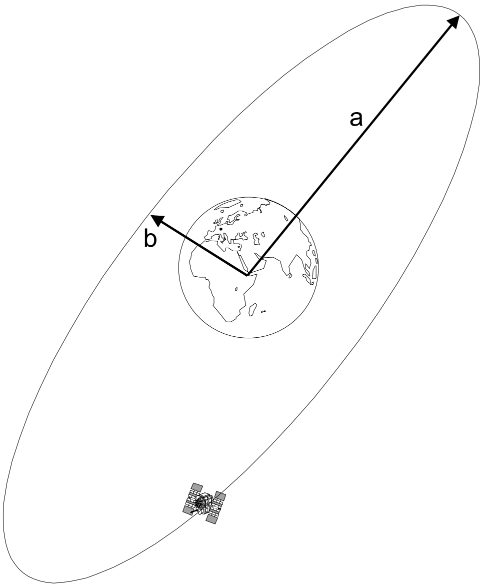

Figure 26: Ephemeris terms

Semi-major axis of orbital ellipse: ***a***

Semi-minor axis of orbital ellipse: ***b***

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

2.6 Upgrading GPS

2.6.1 New Modulation Procedure, BOC

In order for all satellites to transmit on the same frequency, the GPS signals are spread out (modulated) with a special code. This code consists of a Pseudo Random Noise Code (PRN) of 1023 zeroes or ones and is known as the C/A-Code. The code, with a period of 1 millisecond, has a chiprate of 1.023Mbit/s. It is continuously repeated and due to its unique structure enables the receiver to identify from which satellite the signal originates.

The spreading (or modulation) of the data signal is achieved with an exclusive-or (EXOR) operation (Figure 27). The result is referred to as Binary Phase Shift Keying (BPSK(1)). The nominal or baseband frequency signal is generated by one of the atomic clocks and all satellite signals are derived from this. The nominal or baseband frequency is then spread or modulated by the C/A Code at 1 • 1.023Mbit/s.

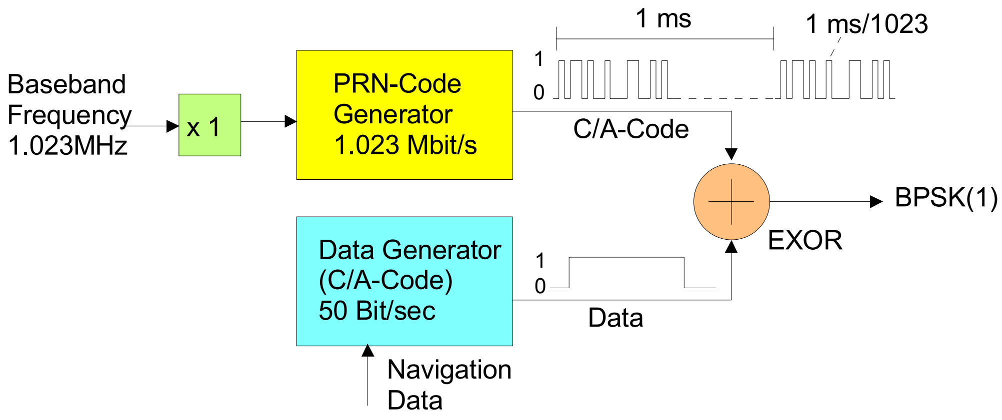

Figure 27: With BPSK the Navigation Data Signal is first spread by a code

In the future, GPS and the European GALILEO systems will use a new modulation process called Binary Offset Code Modulation (BOC). With BOC the BPSK signal undergoes a further modulation [vii]. The Modulation Frequency is always a multiple of the Baseband Frequency of 1.023MHz. The properties of this modulation are communicated in a specific way. For example BOC(10,5) means that the modulation frequency is a factor of 10 times the Nominal or Baseband Frequency (10 • 1.023MHz) and the chiprate of the C/A Code is 5 times the base (5 • 1,023Mbit/s) (Figure 28).

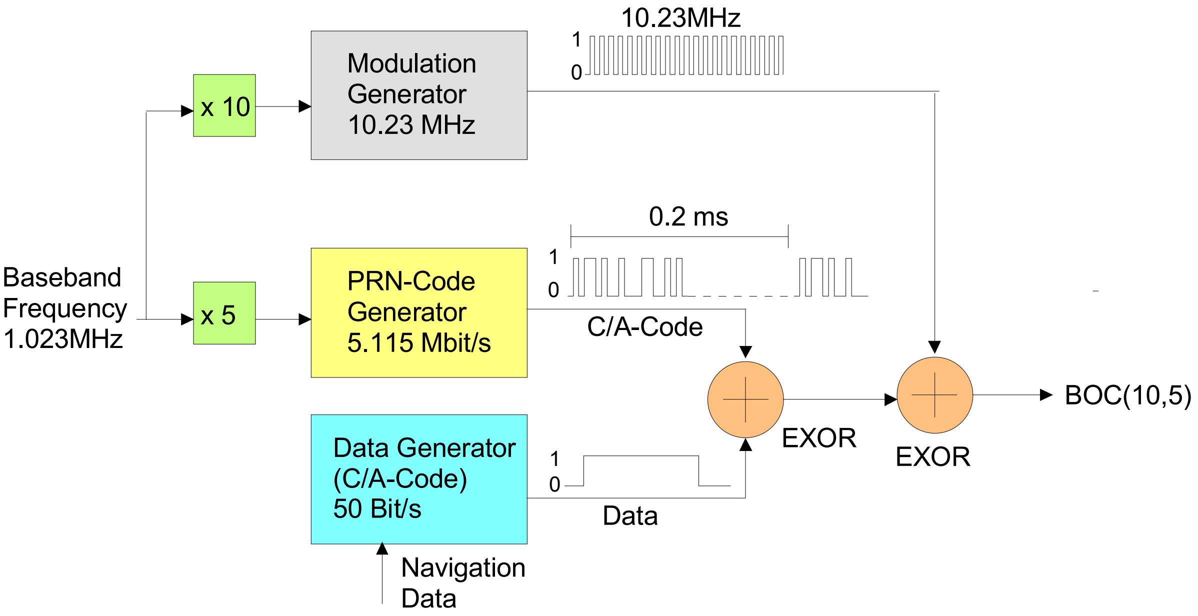

Figure 28: Modulation for the Future: BOC(10,5)

Thanks to BOC the signal will be better distributed over the bandwidth and the influence of opposing signal reflection (Multipath) on the reception of the Navigation Signal will be reduced in comparison to BPSK. When BPSK(1) und BOC(1,1) are simultaneously used their mutual influence is a minimum because the maxima of the power densities are separated (Figure 29).

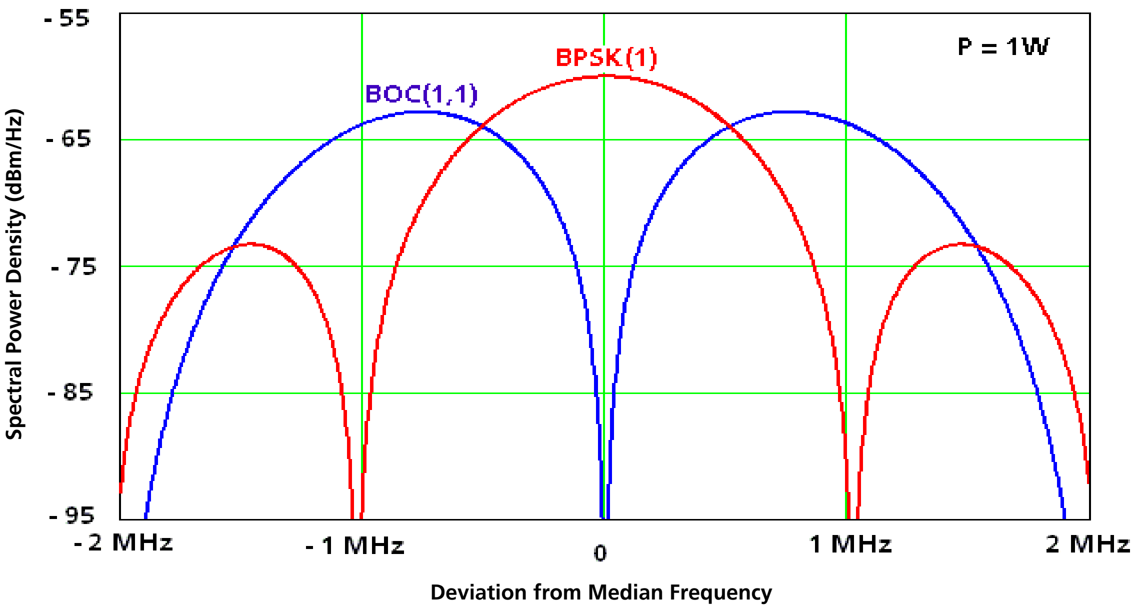

Figure 29: With BPSK(1) and BOC(1,1) the signal maxima are separated (signal strength normalized at 1 W per signal)

2.6.2 GPS Modernization

Since the activation of the GPS system in 1978 all the satellites transmit the following three signals to the Earth:

- On the L1-Frequency (1575.42MHz): one civilian signal (SPS-Service with the C/A-Signal, BPSK(1)) and one military signal (PPS-service with the P(Y)-Signal, BPSK(10))
- On the L2-Frequency (1227.60MHz): a second military signal.

The U.S.DoD has planned incremental improvements to the GPS signal structure (Figure 30). For civilian applications the introduction of a second and third frequency is very important; when more frequencies can be used for establishing position, then the influence of the ionosphere on the signal travel time can be compensated or even eliminated. This compensation is possible because the transmission velocity c in the ionosphere is dependant on the frequency. In addition to the two new signals, the modernization of GPS will provide an increase in the signal strength for civilian users as well as additional capabilities for military applications.

On September 25, 2005 the first of eight new satellites of the type IIR-M (Block 2, Replenishment and Military) was sent into orbit. On December 16, 2005 the satellite was ready for transmission. The launches of the remaining seven satellites began in early 2006. These new satellites transmit additionally:

- A new civilian signal at 1227.60MHz, the so-called L2C Frequency.
- Supplementary military signals at 1575.42MHz and 1227.60MHz: the M Signals, using BOC(10,5) modulation.

A new generation of satellites is planned towards the end of this decade. This new series will have the designation IIF (Block 2, Follow-ON) and III (Block 3). The most important characteristics of these new satellites will be:

- New civilian signal at 1176.45MHz (L5 Frequency). This signal should be more robust than previous civilian signals and can be used in aviation during critical approaches.
- Increase in the signal strength of the M Signals (= M+) through the use of concentrating beam antennas.
- Improvement of the C/A Signal Structure for the civilian L1 Frequency. (To be designated L1C).

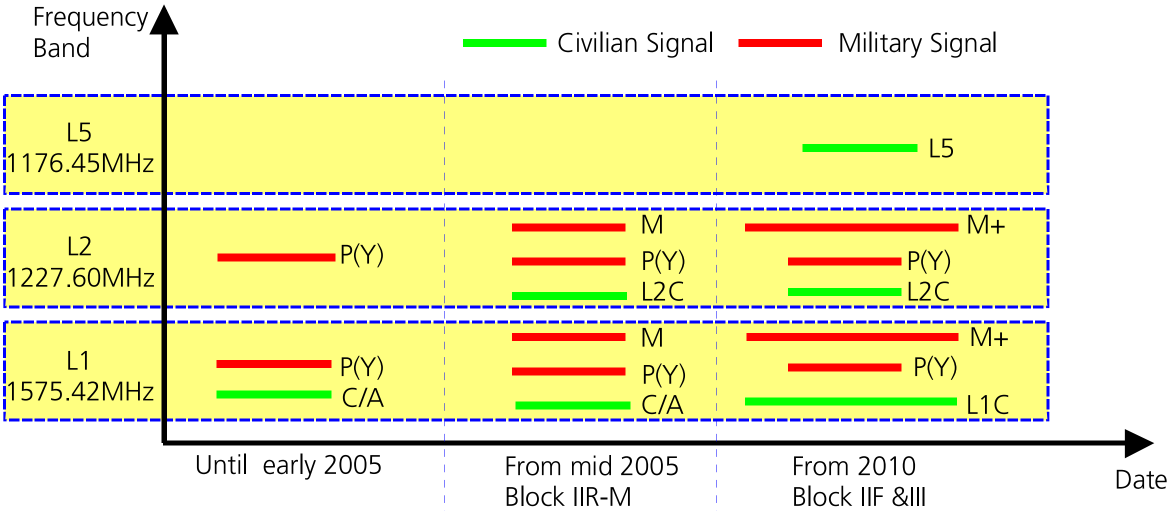

Figure 30: With Modernization the availability of GPS frequencies will be increased

The GPS ground stations will also be renewed. The entire development should be complete and operational by the middle of the next decade. The new signals will then be completely available to users.

3 GLONASS and GALILEO

Do you want to . . .

- know, how the Russian Navigation System GLONASS functions
- understand, why GLONASS will be built up
- know, which system Europe will be activating
- understand, why GALILEO will provide different services
- know, what SAR can mean for sailors
- know, how the new modulation process BOC functions

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

3.1 Introduction

On December 28, 2005 the first GALILEO satellite was brought into orbit. The satellite, with the designation GIOVE-A began a new epoch. For the first time Europe is also actively involved in satellite navigation. GPS should receive some competition: Probably within the next five to six years there will be three independent GNSS systems available. The USA will continue to provide GPS, and Russia and the European Union (EU) will respectively offer functional GLONASS and GALILEO systems. With three functioning GNSS systems we will not only be able to achieve more accurate positioning but will also have different functions available.

GPS will also be modernized in the foreseeable future and will therefore become more reliable (see 2.6).

This chapter gives an overview of the not yet completely operational GLONASS system, and the future European GALILEO system.

3.2 The Russian System: GLONASS

GLONASS is an abbreviation for a GNSS system currently operated by the Russian Defense Ministry. The designation GLONASS stands for **Glo**bal **Na**vigation **S**atellite **S**ystem. The program was first started by the former Soviet Union, and is today under the auspices of the Commonwealth of Independent States (CIS). The first three test-satellites were launched into orbit on October 12, 1982.

The most important specifications of this system were:

- 24 planned satellites (21 standard + 3 reserve satellites). This number has never been achieved. The relatively short lifespan of the individual satellites of 3 to 4 years hampered the completion of the system.
- 3 orbital levels with an angle of 64.8° from the equator (this is the highest angle of all the GNSS systems and allows better reception in polar regions)
- Orbital altitude of 19,100 km
- Orbital period of 11h15.8min
- Every GLONASS satellite transmits two codes (C/A and P-Code) on two frequencies. Every satellite transmits the same codes (PRN), but at different frequencies in the vicinity of 1602MHz and 1246 MHz. These assigned frequencies should be changed in the course of the next years

3.2.1 Completion of GLONASS

The completed GLONASS system will require 24 functional satellites. Due to political instability in the former Soviet Union and many other delays and failures, there were as of August 18, 2006 only 14 operational satellites in orbit [viii]. The CIS plans to have its system functioning by the end of 2008. Three replacement satellites were successfully launched on December 25, 2005. Two of these three satellites are of the M series, which should have a lifespan of 7-8 years. These new satellites transmit 2 civilian signals. After 2007 the first of the K series of satellites are to be launched. These are expected to have a lifespan of 10-12 years and transmit three civilian signals.

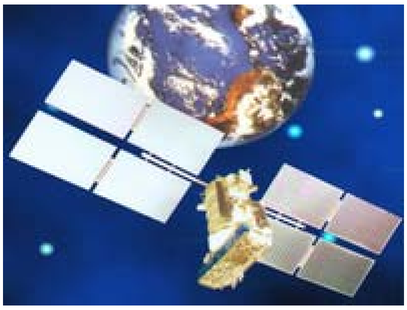

Figure 31: GLONASS-M Satellite (Source ESA)

Figure 32: Proton launch vehicle

3.3 GALILEO

3.3.1 Overview

GALILEO is the European GNSS system. The European Union (EU), in close cooperation with the European Space Agency (ESA), is developing this. The EU and the ESA have together founded an umbrella organization: GALILEO Joint Undertaking (GJU, headquartered in Brussels). GJU oversees and coordinates all phases of development, testing and implementation. GJU guarantees that a single body is responsible for the administration of this program.

The governments of Germany, Italy, France, the UK, Spain and Belgium assume approximately 85% of all the costs.

GALILEO will consist of a constellation of the satellites on 3 circular orbitals at an altitude of 23,616 km above the Earth. These satellites are to be supported by a worldwide network of ground stations.

The key arguments for introducing GALILEO were:

- **To attain independence from the USA.** Worldwide there are two satellite navigation systems: The American GPS and the Russian GLONASS. Both were conceived with military criteria. Until now the Russian system has not brought any usable civilian applications so that GALILEO would be the only alternative to the de facto monopoly of GPS and the American industry. GPS is controlled by the American government which can in the event of a crisis locally downgrade or even deactivate the system. This subjection to the Americans doesn't suite the Europeans. However, the US military has already announced that in times of emergency it is prepared to disrupt GALILEO if this would serve in the interest of American security.
- **To increase the accuracy of positioning.** GALILEO is planned to be more accurate than GPS. It is expected that the open service, OS will provide a precision of approximately 4 to 15m. Critical security services should have a precision of 4 to 6m. Sensitivity to multipath reception will also be reduced. This improvement will be achieved through the application of BOC modulation. GPS will also introduce BOC when it is modernized.
- **To have a purely civilian navigation system.** GALILEO is being conceived and implemented according to civilian criteria; however, it also provides necessary security functions. Contrary to the militarily oriented GPS, GALILEO guarantees the function of individual services.
- **Providing more services.** GALILEO will offer five different functions. In comparison, GPS at the moment offers only two. In the course of modernization, the number of GPS services for civilian applications will also increase.
- **Offer a Search and Rescue Function.** Search and Rescue (SAR) functions are already being offered by other organizations. New with GALILEO is that an alarm can be acknowledged.
- **Increased Security through Integrity Messages.** GALILEO will be more reliable in that it includes an integrity message. This will immediately inform users of errors that develop. On top of this is a guarantee of availability. For the Open Service there will be neither the availability guarantee nor the integrity messages. These services are only available through EGNOS[9].
- **Creation of Employment.** Experts estimate that by the year 2020, the European satellite system GALILEO will generate between 130,000-180,000 jobs. With an initial investment of six billion Euros (at the beginning of the project this was projected at three billion), GALILEO is expected to bring a return of seventy four billion Euros [ix].
- **Attain GNSS Know-How.** Most manufacturers of satellite navigation systems are currently located in the USA. Satellites and satellite accessories, navigation receivers, measuring devices, etc. are predominantly developed and marketed from outside of Europe. With GALILEO, Europe should acquire expertise and provide the domestic industry with a sustainable growth in competence.
- **To improve the worldwide coverage of satellite signals.** GALILEO will offer better reception than GPS to cities located in higher latitudes. This is possible because the GALILEO satellites have orbits at an angle of 56° from the equator as well as an altitude of 23,616km. In addition, modern GNSS receivers are able to

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[9] **E**uropean **G**eostationary **N**avigation **O**verlay **S**ervice

evaluate GPS and GALILEO signals. This multiplies the number of visible satellites from which signals can be received, increasing the level of coverage and the accuracy.

3.3.2 Projected GALILEO Services

For certain critical applications GALILEO will provide information about the system integrity in order to assure the accuracy of positioning. Integrity is understood to be the reliability of information and data provided. Users will quickly (within 6 seconds) receive a warning when the system accuracy falls below the given minima. The GALILEO operators are of the opinion that these warnings are provided soon enough even for critical applications (e.g. aircraft landings). Each service provides different demands on function, accuracy, availability, integrity and other parameters.

3.3.2.1 Open Service, OS

Open Service (OS) is foreseen for mass-market applications. It provides free signals for the determination of position and time. Applications with lower demands for accuracy will use cheaper single-frequency receivers. Because the transmitted frequencies from GALILEO and GPS (L1) are the same for this application, navigation receivers will be able to combine the signals. Due to the increase in the number of satellite signals received there will be an improvement in the reception properties even in suboptimal conditions (e.g. in urban environments). OS will not be provided with System Integrity Information and the GALILEO operators make no guarantees of availability and accept no liability.

3.3.2.2 Commercial Service, CS

The Commercial Service (CS) is envisaged for market applications with higher performance demands than the OS. CS is designed to provide a variety of beneficial services to its customers on a fee for usage basis. Typical examples of these applications would be services providing high-speed data transmission, guarantees of availability, exact-time related services, as well as local correction signals for maximal in positioning accuracy.

3.3.2.3 Safety of Life Service, SoL

The Safety of Life Service (SoL) is envisaged primarily for transportation applications for which an impairment of the navigation system without adequate warning could result in a life-threatening situation. The primary difference to OS is the worldwide high level of information integrity provided to such crucial applications as maritime navigation, aviation and rail traffic. This service is only accessible by using a certified double frequency receiver. To achieve the necessary signal protection SoL will be deployed using the aviation communication channels (L1 and E5).

3.3.2.4 Public Regulated Service, PRS

GALILEO is a civilian system that will also provide stable and access-protected services for governmental (including military) purposes. The Public Regulated Service (PRS) will be available to such clients as police and fire departments and border patrols. Access to this service is restricted and controlled by a civilian agency. The PRS must be available continually and under all conditions, especially during crisis situations where other services can be disrupted. The PRS will be independent of the other services and will be characterized by a high level of signal stability. PRS will also be protected against electronic interference and deception.

3.3.2.5 Search and Rescue, SAR

The SAR service will be used by humanitarian search and rescue services. Emergency transmitters and satellites enable the location of individual persons, crafts and vehicles in aviation, land and maritime emergencies. At the end of the 1970s the USA, Canada, the USSR and France developed a satellite system for the location of activated distress beacons. The system is referred to as SARSAT (**S**earch **A**nd **R**escue **S**atellite-**A**ided **T**racking). The Russian name for the system is “COSPAS”. The COSPAS-SARSAT system employs six LEO (Low Earth Orbit) and five GEO (geostationary) satellites. The GALILEO-SAR service is planned to expand and improve the existing COSPAS-SARSAT system [**X**] in the following ways:

- Almost instantaneous reception of emergency calls from any location on Earth (currently there are delays of an average of one hour).

- Exact determination of position of the distress beacons (to within meters instead of the current accuracy of 5 km).
- Improved effectiveness of the Space Segment through the availability of more satellites to overcome localized hindrances during suboptimal conditions (30 GALILEO satellites in medium orbitals will supplement the existing LEO and GEO satellites of the COSPAS-SARSAT system).

GALILEO will introduce a new SAR function; the distress signal reply (from the SAR operator to the emergency transmitter radio) will begin. This should simplify rescue measures and reduce the number of false alarms. The GALILEO SAR service will be defined in cooperation with COSPAS-SARSAT, with the characteristics and functions of the service being governed by the IMO (International Maritime Organization) and ICAO (International Civil Aviation Organization).

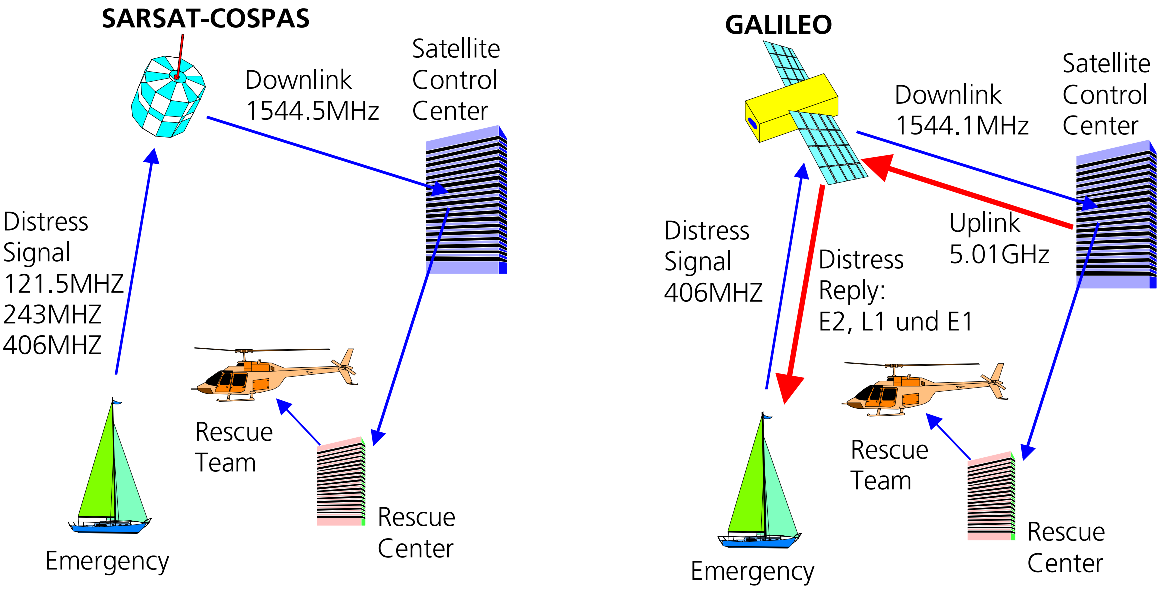

Figure 33: Unlike SARSAT-COSPAS, GALILEO's Search And Rescue service also provides a reply to the distress signal

3.3.3 Accuracy

Depending on the service GALILEO will provide differing levels of accuracy [xi]. When two frequency receivers are used the accuracy can be improved by compensating for signal travel time errors caused by ionospheric conditions. By utilizing local measures (e.g. DGPS) the precision can be increased to within centimeters. Table 3 shows the anticipated accuracy of 95% of all measurements.

Service	Receiver Type	Horizontal Positioning Accuracy	Vertical Positioning Accuracy
OS	Single Frequency	15m	35m
	Double Frequency	4m	8m
CS	Double Frequency	<1m	<1m
PRS	Single Frequency	6.5m	12m
SoL	Double Frequency	4-6m	4-6m

Table 3: Planned positioning accuracies for GALILEO

3.3.4 GALILEO Technology

The space segment of GALILEO will consist of 30 satellites (3 of which will be active reserve satellites). They will be placed in circular orbits at an altitude of 23,616 km providing for worldwide coverage. The satellites (each with a weight of 680 kg and dimensions of 2.7 m x 1.2 m x 1.1 m) will be evenly distributed over 3 orbitals, having an angle of 56° to the equator (Figure 34) and an orbital period of 14 hours and 5 minutes.

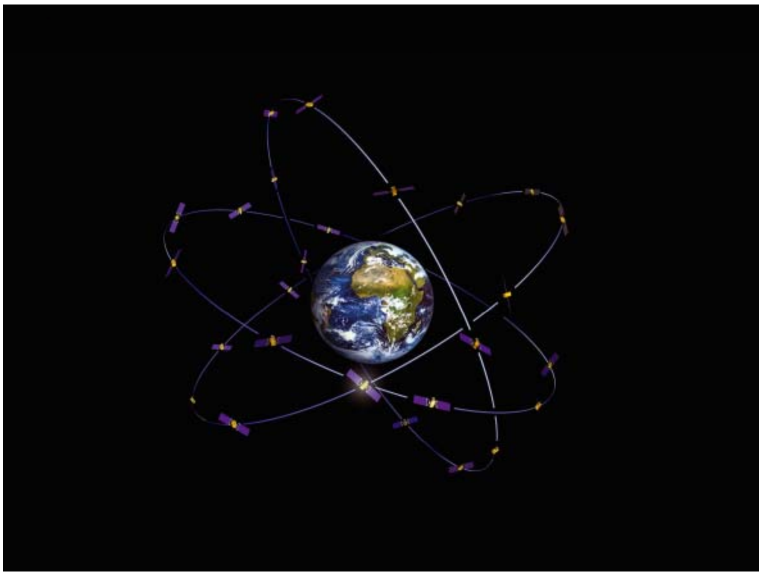

Figure 34: Constellation of the GALILEO satellites (picture: ESA-J.Huart)

The GALILEO satellites are expected to have an operational lifespan of 15 years. The required power of 1500 W will be generated by large area solar panels. In order to maintain current navigation data, the satellites will be in radio contact to the ground segment of the system at regular intervals of 100 minutes.

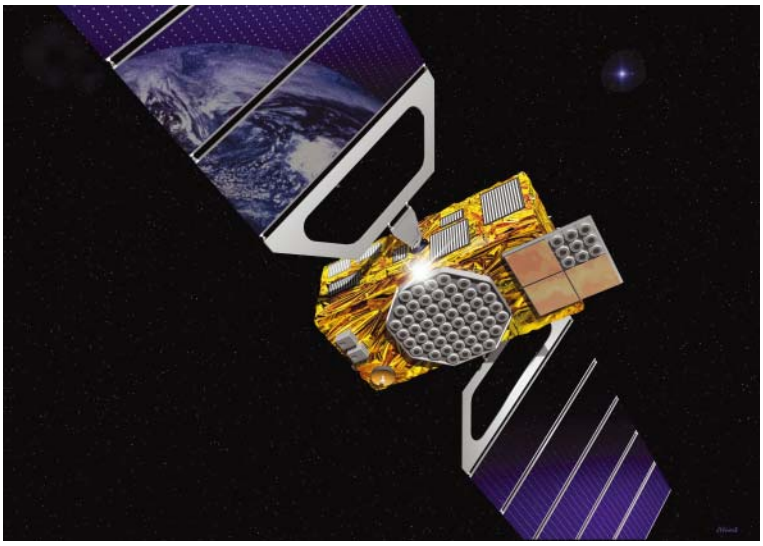

Figure 35: GALILEO satellite (Picture: ESA-J.Huart)

The ground segment of the system will consist of a series of control centers, together with a global network of stations for various tasks. This includes the monitoring of signal integrity and the coordination of the foreseen extensive Search and Rescue services.

There are worldwide control centers planned for navigation and satellite control. The core of the ground segment will consist of two GALILEO control centers in Germany and Italy [xii]. The main control center will be the German Aerospace (DLR) Center at Oberpfaffenhofen. From there the control of normal operation of the 30 satellites is planned for at least 20 years. A second comprehensive control center with its own specific responsibilities for normal operation will be located at Fucino in Italy. This is also to be a backup to the main control center in the event of any problems that should arise there. Control of the positioning of the 30 satellites will be evenly divided between the European Satellite Control Center (ESA/ESOC) in Darmstadt, Germany, and the French National Space Studies Center (CNES) in Toulouse, France. A chain of about 30 Integrity Monitoring Stations (IMS) distributed worldwide will control the integrity of the satellite signals. Two control centers will evaluate the IMS information and sound an alarm in the event of an excessive deviation in position data.

It is planned that three Arianne 5 rockets, each carrying eight satellites (Figure 36), and three Soyuz rockets, each carrying two GALILEO satellites will transport the satellites into Middle Earth Orbit (MEO).

Figure 36: Ariane 5 Rocket delivering 8 GALILEO satellites into space (GALILEO-industries.net)

3.3.4.1 Signal Frequencies

Depending on the services, there will be different frequencies, modulation forms, and data transmission rates used (See Table 4 and Figure 37). The principal modulation forms will be BPSK and BOC. As an exception E5a and E5b employ a slightly modified version of BOC modulation known as AltBOC.

Band: Frequency (MHz)	Signal Name	Frequency of Maxima (MHz)	Services	Modulation	Data Rate (Bit/s)
E5: 1191.795	E5a	1176.45	OS, CS	AltBOC(15, 10)	50
	E5b	1207.14	OS, CS, SoL	AltBOC(15, 10)	250
E6 : 1278.75	E6b	1278.75	CS	BPSK(5)	1000
	E6a	1268.52 & 1288.98	PRS	BOC(10, 5)	100
L1: 1575.42	L1B	1574.397 & 1576.443	OS, CS, SoL	BOC(1, 1)	250
	E2 & E1	1560.075 & 1590.765	PRS	BOC (15, 2.5)	100

Table 4: Frequency plan of GALILEO and distribution of services

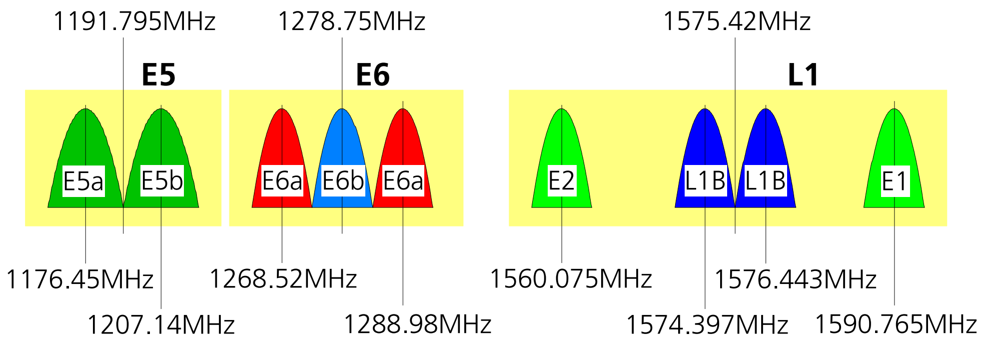

Figure 37: Frequency Plan for GALILEO

Additionally E5a, E5b, E6 and L1 transmit a pilot channel. The pilot channel is free of navigation data and the phase is shifted at 90° to the other signals. This reduces the acquisition time of the receiver.

Above all in the L1 band, GALILEO and GPS will need to share frequencies. In this band GPS has 3 signals: C/A-Signal, P(Y)-Signal and the new M-Signal. GALILEO will only use two signals: the L1B-Signal and the E2/E1 pair. The common use of this frequency band has at times brought about intense conflicts. It was not until June 2004 that the USA and the EU could come to agreement on assignment and modulation forms on this frequency.

In Figure 38 the power density of the signals on the L1 band are depicted, with the assumption that the power of all of the signals is the same (standardized at 1W).

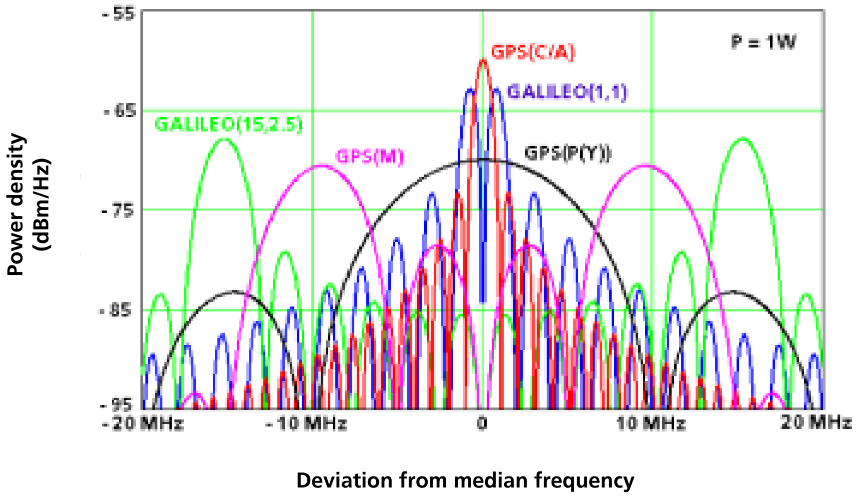

Figure 38: The L1 band will be intensively used by GALILEO and GPS (Power Density standardized at 1 W per signal)

3.3.4.2 Time Frame

On June 26, 2004, after many years of difficult negotiations, the USA and the EU were able to sign an agreement in Dublin. The goal of the agreement was to secure the smooth cooperation (interoperability) and compatibility of GALILEO and its American counterpart GPS. Contentious issues such as frequency assignment and modulation forms were also regulated. This should make future close coexistence of GALILEO and GPS possible. On December 10, 2004, upon the recommendation of the European Commission, the European Council confirmed the technical characteristics of the system (with emphasis on the services to be offered [xiii]). The Council addressed the transition from the implementation phase (2006-2008) to the operational phase and confirmed the participation of the EU in the financing of these two phases. According to the European Commission GALILEO should become operational in 2008. Commercial operations will probably not begin until 2012.

The corporation operating GALILEO will have its seat in Toulouse and London [xiv].

The construction of the system will take place in four phases:

- **Project definition:** The goal of the definition phase was to establish the fundamental parameters and specifications of the system. This part of the overall project was completed in 2003.
- **Development and tests in orbit:** On December 28, 2005, the first experimental satellite GIOVE-A was launched into orbit from the Russian Cosmodrome at Baikonur in Kasachstan (Figure 39). GIOVE is an acronym for **G**ALILEO **I**n-**O**rbit **V**alidation **E**lement as well as being the Italian name for the planet Jupiter. On January 12, 2006, GIOVE-A transmitted its first signals. The signals were registered and analyzed at the Observation Station for Atmospheric and Radio wave Research in Chilbolton in Britain as well as the ESA ground station at Redu in Belgium [**XV**]. The second experimental satellite GIOVE-B will be launched into orbit by the end of 2007. With GIOVE-A and B the EU will secure the frequency bands for GALILEO operation and determine the orbitals for the test phase satellites. These pioneer satellites will also serve in the testing of important technology, such as atomic clocks, in the hard conditions of space. GIOVE-A has two Rubidium atomic clocks (with a stability of approximately 10 nanoseconds per day) and GIOVE-B will have two passive Hydrogen-Maser atomic clocks (with a stability of less than 1 nanosecond per day) onboard. Should the experimental phase with GIOVE-A and GIOVE-B be successful, four satellites will be launched into orbit and tested (the satellites were ordered on December 21, 2004). With this "minimum constellation" scientists can test if the satellites can deliver exact position and time data to test locations on the ground. The entire test phase in space should be completed by 2008, with the total costs of the project definition and testing phase amounting to € 1.1 billion ($US 1.4 billion).

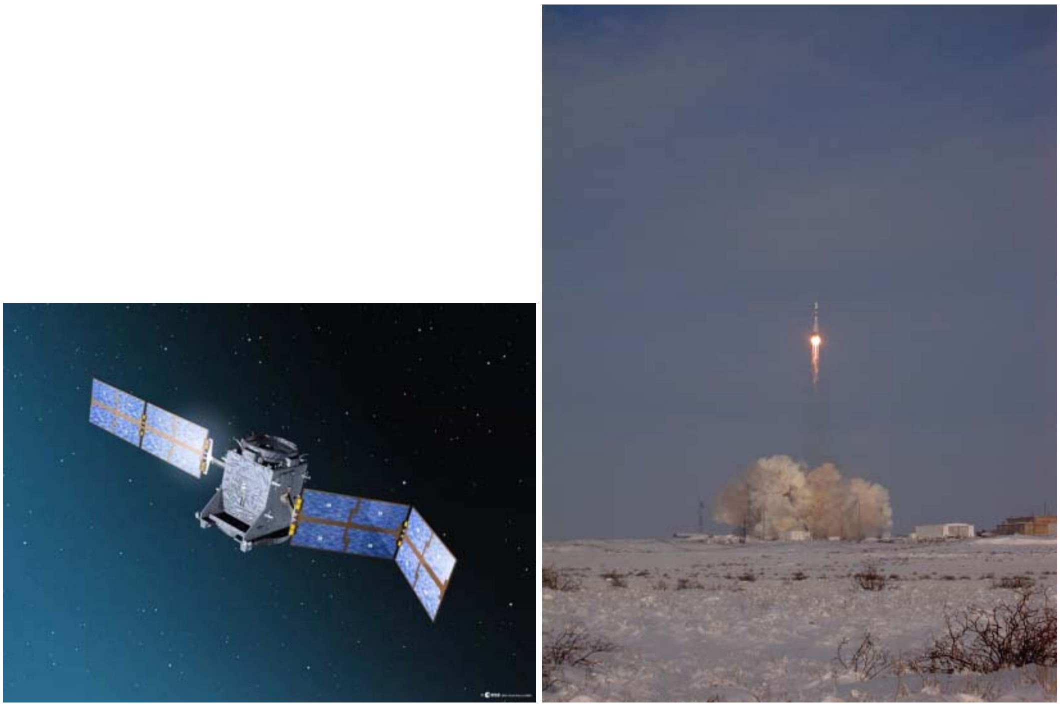

Figure 39: GIOVE-A and its launch on December 28, 2005 (PictureESA)

- **Implementation and start-up of complete system:** If the results of the first two phases are positive, the system will then be built up for full operation. The remaining satellites (four should by this time already be operational) will be finished and launched into orbit and the necessary ground stations completed. The planned timeframe is for completion by 2011 with total costs of € 2.1 billion ($US 2.75 billion). Of this 1/3 is to be publicly financed and 2/3 financed by the private sector.
- **Use:** As soon as all the satellites are in orbit the system can begin operation. At the end of the build-up phase there should be 27 operations and 3 reserve satellites in orbit. The ground stations as well as local and regional service stations will be constructed. The annual operations costs have been estimated at € 220 million ($US 288 million) of which the public sector will overtake an exceptional sum of € 500 million ($US 655 million) during the start-up years. In the following years these costs shall be completely assumed by the private sector.

On January 12, 2006 the Republic of Korea committed itself to participating in the GALILEO system. It is the sixth country outside of the EU after Morocco, China, Israel, the Ukraine and India to participate in GALILEO. Negotiations are currently ongoing with Argentina, Australia, Brazil, Canada, Chile, Malaysia and Mexico. Other African and Asian countries have also expressed their interest in participating. [xvi].

3.3.5 Most Important Properties of the three GNSS Systems

Table 5 lists the most important properties of the three existing (resp. planned) GNSS systems.

	GPS	***Glonass***	***GALILEO***
Start of development	1973	1972	2001
1st Satellite Launch	Feb. 22, 1978	October 12, 1982	December 28, 2005
Number Satellites	Minimum: 24 / Maximum: 32	Planned: 24 + 3 passive reserves	Planned: 27 + 3 active reserves
Orbitals	6	3	3
Inclination	55°	64.8°	56°
Altitude	20,180 km	19,100 km	23,616 km
Orbital Period	11 hours 58 min	11 hours 15.8 min	14 hours 5 min
Geodetic Data	World Geodetic System 1984 (WGS 84)	Parametry Zemli 1990 (PZ-90)	Galileo Terrestrial Reference Frame (GTRF)
Time System[10]	GPS-Time	Glonass-Time	GST (GALILEO System Time)
Signal Characteristic	CDMA[11]	FDMA[12]	CDMA
Frequencies	2 frequencies, with with a 3rd frequency planned	24	2 frequencies, with with a 3rd frequency planned
Encryption	Military Signal	Military Signal	CS and PRS services
Services	2 (civilian + military) / 4	2 (civilian + military)	5
Responsibility	US Department of Defense	Russian Defense Ministry	Civilian Governments of the EU
Integrity Signal	Currently none but planned	none	Planned

Table 5: Comparison of the most important properties of GPS, GLONASS and GALILEO

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[10] Deviation from UTC is indicated

[11] Code Identification: Code is different for every satellite

[12] Frequeny Identification: Frequeny is different for every satellite

4 Calculating Position

If you would like to . . .

- understand how co-ordinates and time are determined
- know what pseudorange is
- understand why a GNSS 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 asserted by the GPS system operator

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

4.1 Introduction

GNSS systems combine sophisticated satellite and radio technology to provide navigation receivers with radio signals indicating among other things the time of transmission and the identity of the transmitting satellite. Calculating the position from these signals requires mathematical operations that will be examined in this chapter.

4.2 Calculating a position

4.2.1 The principle of measuring signal travel time (evaluation of pseudorange)

In order for a GNSS receiver to determine its position, it must receive time signals from four separate satellites (Sat 1 ... Sat 4), in order to calculate the signal travel times Δt_1 ... Δt_4 (Figure 40).

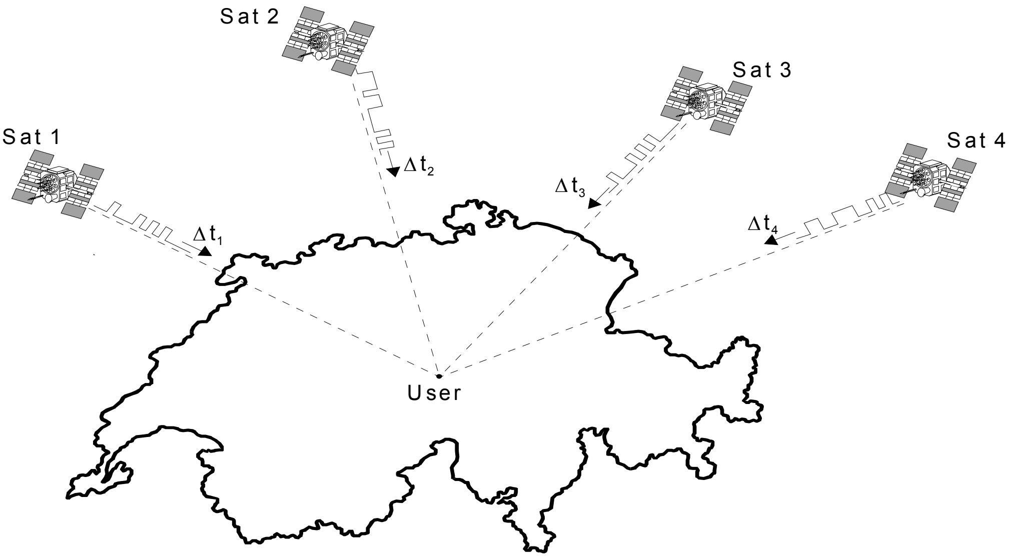


Figure 40: Four satellite signals must be received

Calculations are effected in a Cartesian, three-dimensional coordinate system with a geocentric origin (Figure 41). The range of the user from each of the four satellites R_1, R_2, R_3 and R_4 can be determined with the help of signal travel 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.

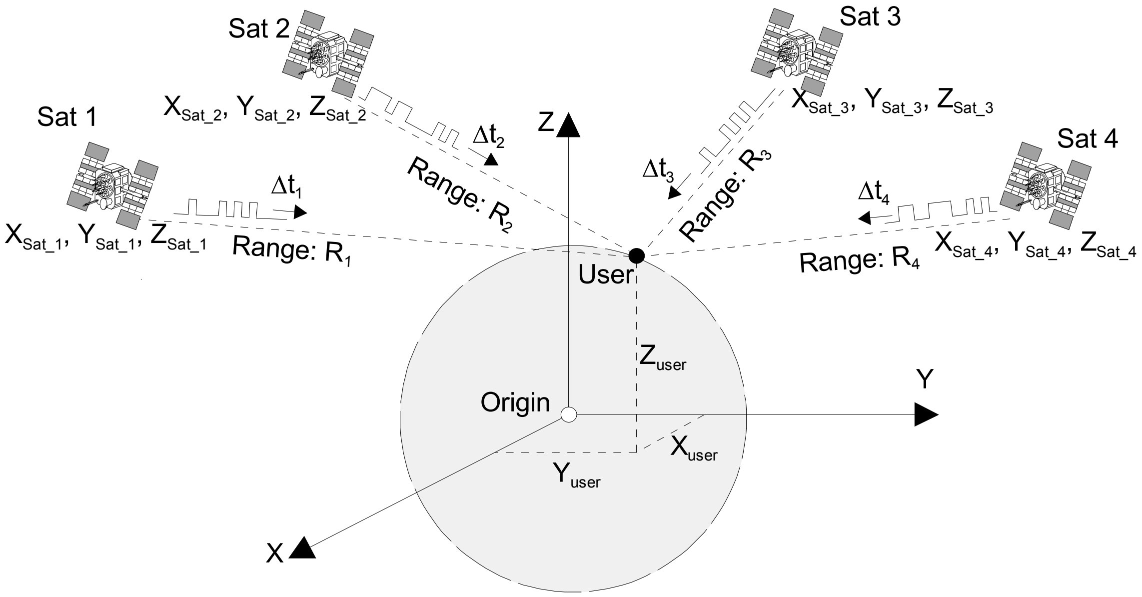


Figure 41: Three-dimensional coordinate system

Due to the atomic clocks onboard the satellites, the time at which the satellite signal is transmitted is known very precisely. All satellite clocks are adjusted or synchronized with each other and UTC (universal time coordinated). In contrast, the receiver clock is not synchronized 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 travel time and the distance R. As a result, an incorrect distance is measured that is known as pseudo distance or pseudorange PSR [xvii].

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

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

$$\mathrm{PSR} = \mathrm{R} + \Delta t_0 \cdot \mathrm{c} \tag{3a}$$

R:	true range of the satellite from the user
c:	speed of light
Δt:	signal travel time from the satellite to the user
Δt_0:	difference between the satellite clock and the user clock
PSR:	pseudorange

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)

$$\mathrm{PSR} = \sqrt{(X_{Sat} - X_{User})^2 + (Y_{Sat} - Y_{User})^2 + (Z_{Sat} - Z_{User})^2} + c \cdot \Delta t_0 \tag{5a}$$

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

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

$$\mathrm{PSR}_i = \sqrt{(X_{Sat\_i} - X_{User})^2 + (Y_{Sat\_i} - Y_{User})^2 + (Z_{Sat\_i} - Z_{User})^2} + c \cdot \Delta t_0 \tag{6a}$$

4.2.2 Linearization of the equation

The four equations in 6a produce a non-linear set of equations. In order to solve the set, the root function is first linearized according to the Taylor model, the first part only being used (Figure 42).

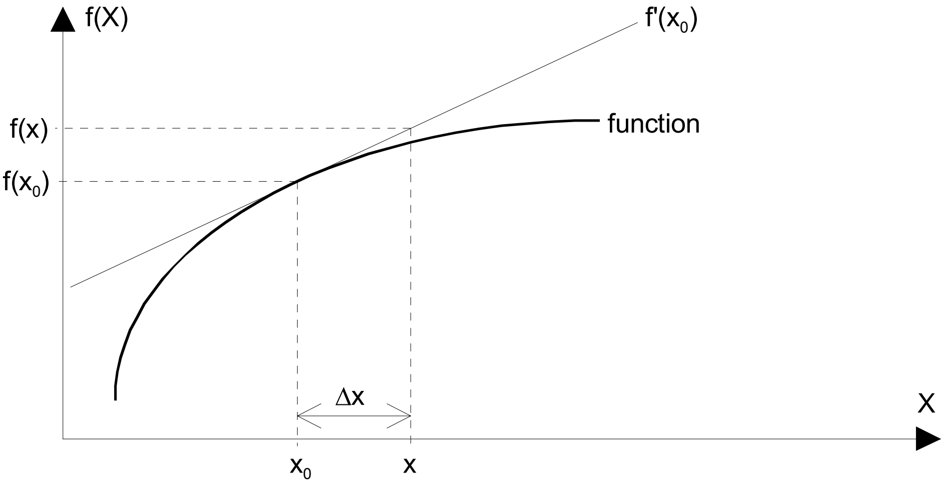


Figure 42: Conversion of the Taylor series

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): $$f(x) = f(x_0) + f'(x_0) \cdot \Delta x \tag{7a}$$

In order to linearize the four equations (6a), an arbitrarily estimated value x_0 must therefore be incorporated in the vicinity of x. This means that instead of calculating X_{User} , Y_{User} and Z_{User} directly, an estimated position X_{Total}, Y_{Total} and Z_{Total} is initially used (Figure 43).

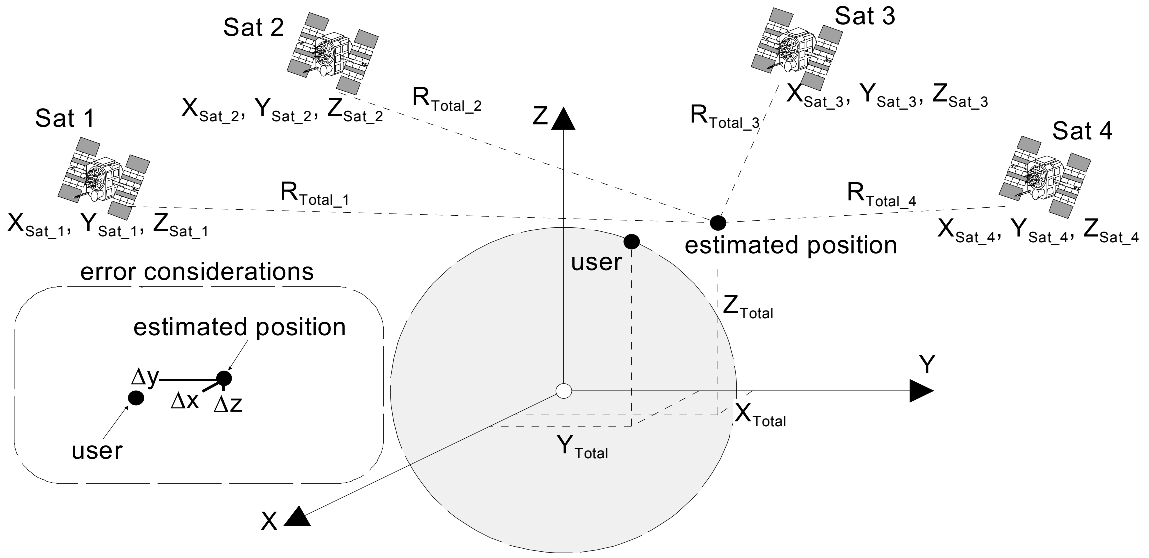


Figure 43: Estimating a position

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

$X_{User} = X_{Total} + \Delta x$

$Y_{User} = Y_{Total} + \Delta y$

$Z_{User} = Z_{Total} + \Delta z$ (8a)

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

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

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

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

After carrying out partial differentiation, this gives the following:

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

4.2.3 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:

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

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

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

$X_{Total\_New} = X_{Total\_Old} + \Delta x$

$Y_{Total\_New} = Y_{Total\_Old} + \Delta y$

$Z_{Total\_New} = Z_{Total\_Old} + \Delta z$ (14a)

The estimated values X_{Total_New} , Y_{Total_New} and Z_{Total_New} 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.

4.2.4 Summary

In order to determine a position, the user (or the user's 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:

$X_{User} = X_{Total\_New}$

$Y_{User} = Y_{Total\_New}$

$Z_{User} = Z_{Total\_New}$ (15a)

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

4.2.5 Error analysis and DOP

4.2.5.1 Introduction

Up until now, the magnitude of error has not been taken into consideration in calculations. In GNSS technology, different causes can contribute to the total error:

- Satellite clocks: although, for example, every GPS satellite is provided with four highly accurate atomic clocks, a time error of only 10 ns is enough to produce a positioning error in the order of magnitude of 3 m.
- Satellite orbits: generally speaking, the exactness of the satellite position is only known up to approximately 1 ... 5 m.
- Speed of light: the signals from the satellites travel at the speed of light. These slow down when crossing the ionosphere and troposphere and cannot, therefore, be assumed to be a constant. This deviation from the normal speed of light creates an error in the calculated position.
- Signal travel time error measurement: the GNSS receiver is only able to determine the time of the incoming satellite signal with limited accuracy.
- Multipath: The error level is further increased by the reception of reflected signals.
- Satellite geometry: determining of position is more difficult if the four reference satellites being used for measurement are too close together. The effect of satellite geometry on measurement accuracy is referred to as **DOP** (**D**ilution **O**f **P**recision) (See Table 6).

There are various causes of measurement error. Table 1 shows the extent of horizontal position errors from different source.

By implementing corrective measures (**D**ifferential **GPS**, **DGPS**) the number of error sources can be eliminated or reduced.

Error cause	**Error without DGPS**	**Error with DGPS**
Ephemeris data	2.1m	0.1m
Satellite clocks	2.1m	0.1m
Effect of the ionosphere	4.0m	0.2m
Effect of the troposphere	0.7m	0.2m
Multipath reception	1.4m	1.4m
Effect of the receiver	0.5m	0.5m
Total RMS value	5.3m	1.5m
Total RMS value (filtered, i.e. slightly averaged)	**5.0m**	**1.3m**

Table 6: Error causes (typical ranges)

4.2.5.2 Effect of satellite geometry: DOP (Dilution of Precision)

Positioning accuracy using GNSS in the navigation mode depends, on the one hand on the accuracy of the measurement of the individual pseudoranges, and on the other hand on the geometrical configuration of the satellites used; expressed through a scalar integer which is termed DOP (Dilution of Precision) in navigation literature.

Various DOP designations are in use:

- GDOP: Geometrical DOP (Position in space including clock drift included in solution)
- PDOP: Position DOP (Position in space)
- HDOP: Horizontal DOP (Position in the horizontal)
- VDOP: Vertical DOP (Only height)

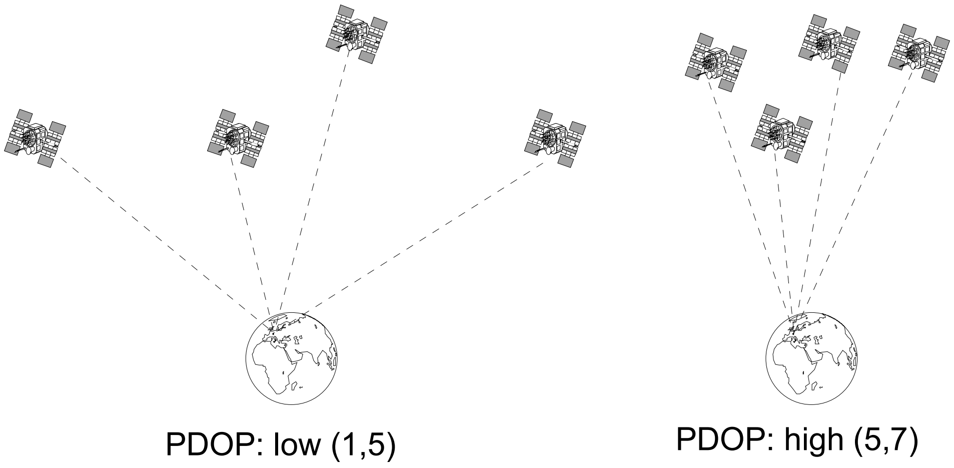


Figure 44:Satellite geometry and PDOP

The DOP value is the reciprocal of the tetrahedron volume that is formed by the satellite and user positions (Figure 44 and Figure 45). The best geometrical situation is produced when the volume is the maximum and thereby the PDOP a minimum.

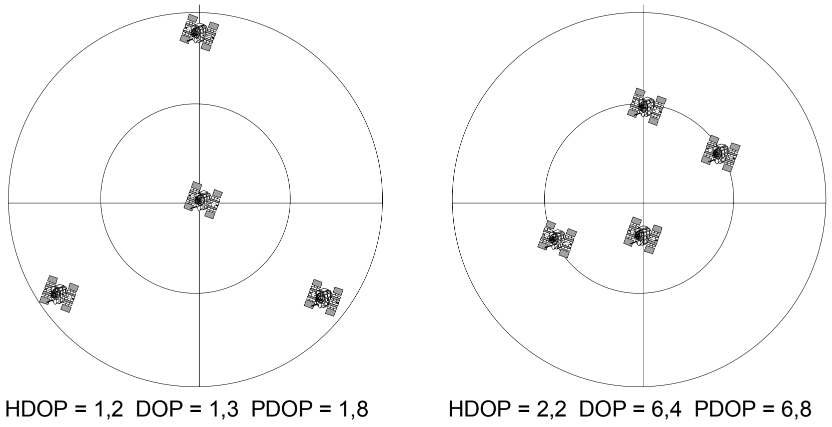


Figure 45: Effect of the satellite constellation on the DOP value

In open areas the satellite coverage is so favorable that the PDOP and GDOP values rarely exceed 3 (Figure 46 and Figure 47).

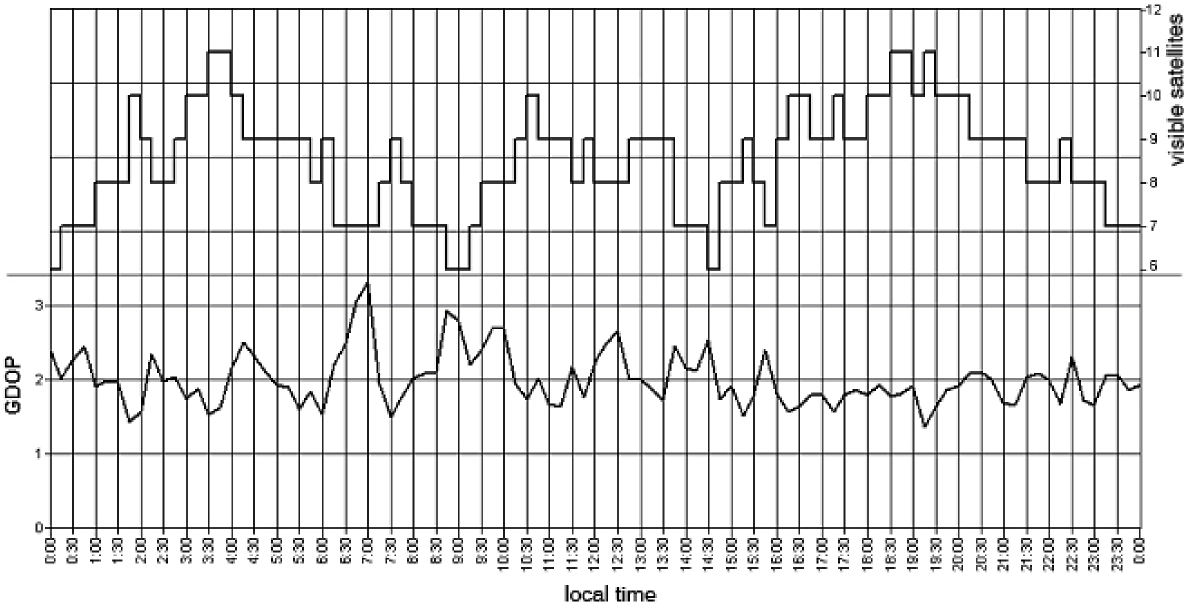


Figure 46: GDOP value and the quantity of visible satellites according to the time

In mountainous areas and in forests the DOP value plays an important role in the planning of measurement campaigns given that there are frequently phases with highly unfavorable geometrical constellations.

As such, it is necessary to plan measurements in accordance with DOP values (e.g. HDOP) or to evaluate the target accuracy in accordance with this, especially since different DOP values appear within the space of a few minutes.

In all planning and calculation programs provided by leading equipment manufacturers, the DOP values can be shown. Figure 27 shows the example of the HDOP course, when there is no shadowing (the maximum HDOP value is approx. 1.9). Figure 48 shows the example of the HDOP course, when there is marked shadowing (here the maximum HDOP value of 20 is exceeded several times!). The area between 180° to 270° is shadowed by a high-rise building and in the area between 270° to 180° the mountain silhouettes are shown.

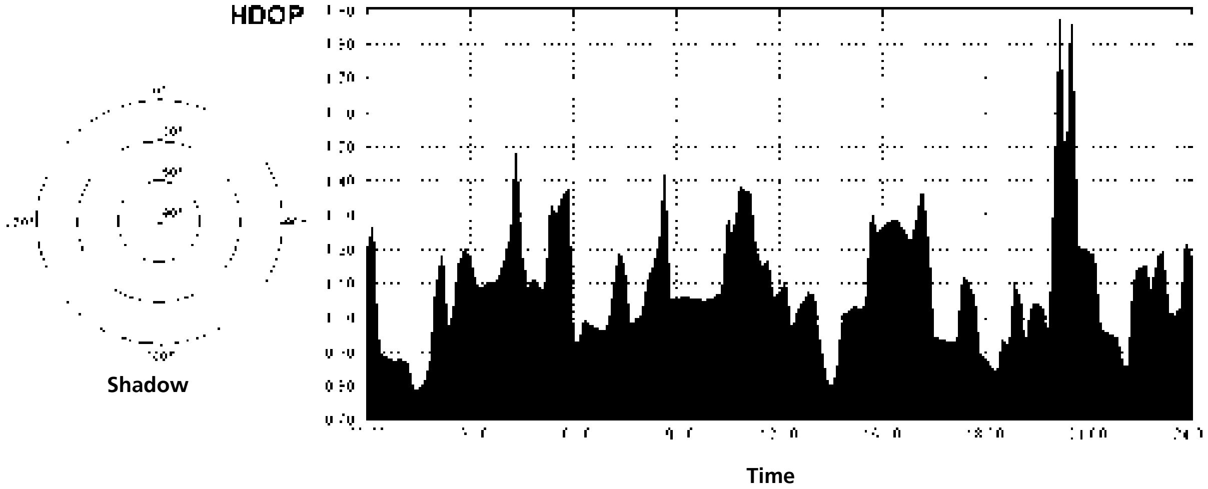


Figure 47: HDOP value over a 24h period, without shadowing (max. value is 1.9)

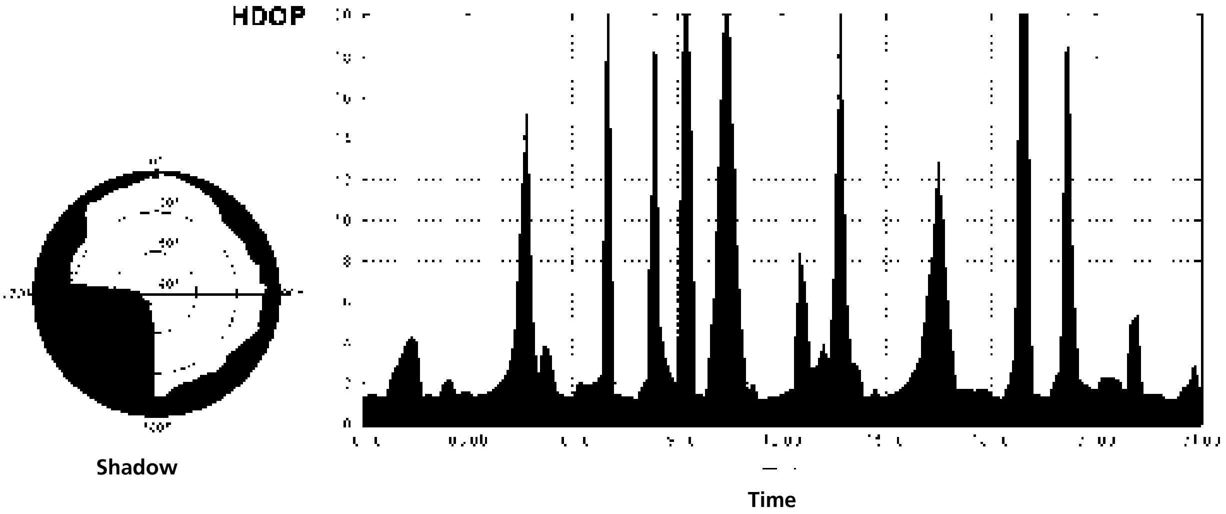


Figure 48: HDOP value over a 24h period, with shadowing (max. value is greater than 20)

In the case of this massive shadowing only a few time slots (See Figure 48) with a favorable DOP value are possible (Less than 2). Time slots with DOP values over 6 should, if at all possible, be avoided.

4.2.5.3 Total Error

Measurement accuracy is proportionally dependent on the DOP value. This means that when the DOP value doubles, the positioning error is also twice as great.

Generally applicable: Error $(1\sigma) = 1 \ast$ Total RMS Value $\ast$ DOP Value

Error $(2\sigma) = 2 \ast$ Total RMS Value $\ast$ DOP Value

In Table 7 the 1 Sigma value ($1\sigma = 68\%$) and the 2 Sigma value ($2\sigma = 95\%$) are given. The values are valid for a medium satellite constellation of HDOP = 1.3. The implementation of suitable correction methods (such as using several linked receivers (**D**ifferential **GPS**, **DGPS** (see chapter 6)) can eliminate or reduce the number of error sources (typically to 1... 2m, 1 Sigma value).

Type of error	Error without DGPS	Error with DGPS
Total RMS value (filtered, i.e. slightly averaged)	5.0m	1.5m
Horizontal error (1 Sigma (68%) HDOP=1.3)	6.5m	2.0m
Horizontal error (2 Sigma (95%) HDOP=1.3)	13.0m	4.0m

Table 7: Total error in HDOP = 1.3

Usually the accuracy is better than shown. Long-term measurements available to the US-Federal Aviation Administration have shown that in 95% of all measurements the horizontal error was less than 7.4m and the vertical error was less than 9.0m. The time period for the measurement was always 24 hours.

The U.S.DoD maintains that their system will provide standard civilian applications with a horizontal accuracy of 13m, a vertical accuracy of 22 m and a time accuracy of ~40ns. By employing additional measures such as, DGPS, longer measuring time, and special measuring techniques (phase measurement), positional accuracy can be increased to within a centimeter.

5 Coordinate 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!*

5.1 Introduction

A significant problem to overcome when using a GNSS system is the fact that there are a great number of differing co-ordinate systems worldwide. As a result, the position measured and calculated does not always correspond with one’s supposed position.

In order to understand how GNSS systems function, it is necessary to examine some of the basics of geodesy: the science that deals with the surveying and mapping of the Earth’s surface. Without this basic knowledge, it is difficult to understand the apparently bewildering necessity of combining the appropriate map reference systems (datums) and grids. Of these there are more than 100 different datums and approx. 10 different grids to select from. If an incorrect combination is made, a position can be out by several hundred meters.

5.2 Geoids

We have known that the Earth is round since Columbus. But how round is it really? Describing the shape of our blue planet has always been an imprecise science. Over the centuries several different models have been presented to represent the true shape of the Earth as faithfully as possible. A geoid is a close approximation of this true shape.

The geometrical “surface” of the Earth is an idealized smooth and level surface set at the average height of sea level. Using the Greek word for Earth, the shape of this surface is described as a geoid (Figure 49).

A geoid can only be defined as a mathematical figure with a limited degree of accuracy and only with certain 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 level for measuring height. For example, the reference point in Switzerland for measuring height is the “Repère Pierre du Niton (RPN, 373.600 m) in the Geneva harbor basin. This height originates from point to point measurements with the port of Marseilles (mean height above sea level 0.00m).

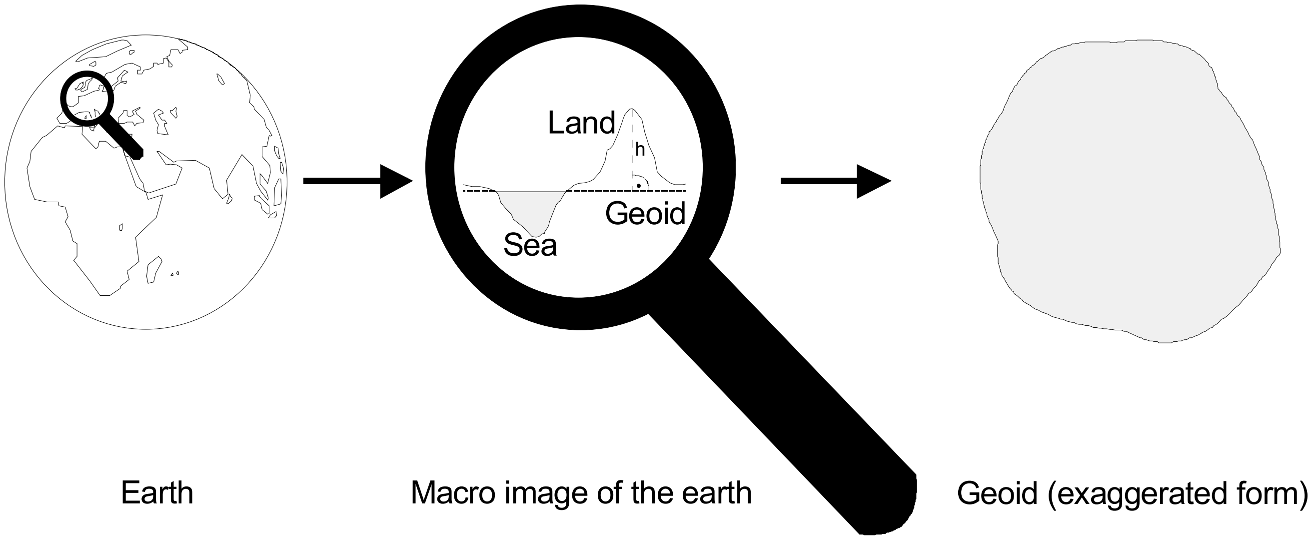


Figure 49: A geoid is an approximation of the Earth's surface

5.3 Ellipsoid and datum

5.3.1 Ellipsoid

A geoid 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 an ellipsoid. If the surface of an ellipse is rotated about its symmetrical north-south pole axis, a spheroid is obtained as a result (Figure 50).

An ellipsoid 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).

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

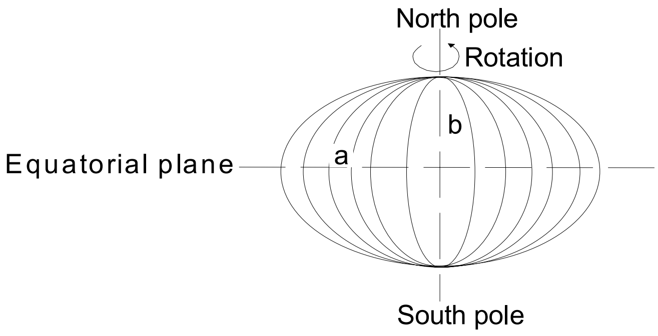


Figure 50: Producing a spheroid

5.3.2 Customized local reference ellipsoids and datum

5.3.2.1 Local reference ellipsoids

When dealing with an ellipsoid, care must be taken to ensure that the natural perpendicular does not intersect vertically at a point with the ellipsoid, but rather with the geoid. Normal ellipsoidal and natural perpendiculars do not therefore coincide, they are distinguished by "vertical deflection" (Figure 52), 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 customized non-geocentric ellipsoid as a reference surface for carrying out surveying operations (Figure 51). The semi axes a and b as well as the mid-point are selected in such a way that the geoid and ellipsoid match national territories as accurately as possible.

5.3.2.2 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 GNSS receivers, care should be taken to ensure that the relevant map reference system has been entered into the receiver.

There are over 120 map reference systems available, such as: CH-1903 for Switzerland, NAD83 for North America, and WGS-84 as the global standard.

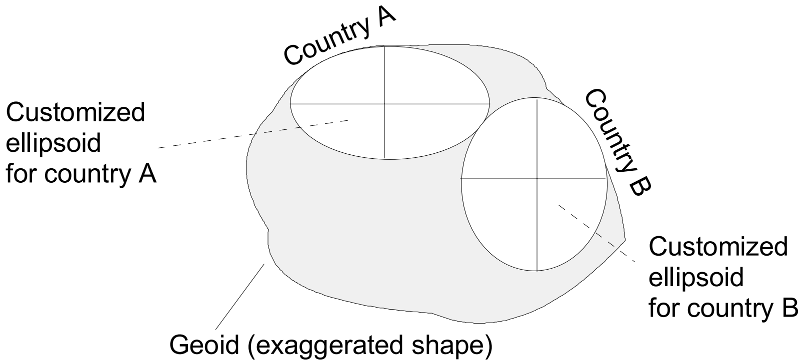


Figure 51: Customized local reference ellipsoid

An ellipsoid 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 52).

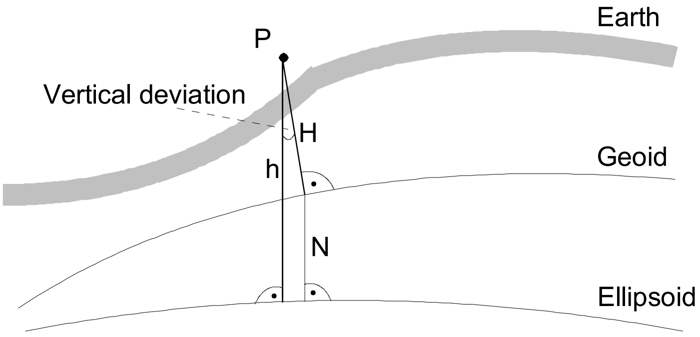


Figure 52: Difference between geoid and ellipsoid

5.3.3 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 summarized in the following table (Table 8). 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 8: National reference systems

5.3.4 Worldwide reference ellipsoid WGS-84

The details displayed and calculations made by a GNSS 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 ellipsoid (Figure 53) 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.

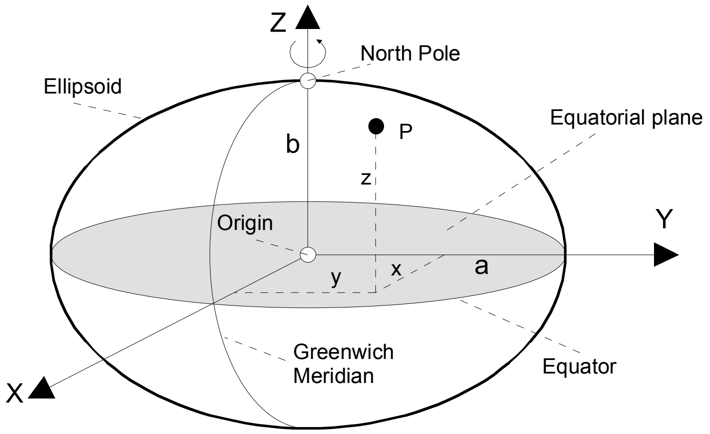


Figure 53: Illustration of the Cartesian co-ordinates

Parameter of WGS-84 Reference Ellipsoids

Semi major axis a (m)	Semi minor axis b (m)	Flattening (1: ....)
6,378,137.00	6,356,752.31	298,257223563

Table 9: 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 54). 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.

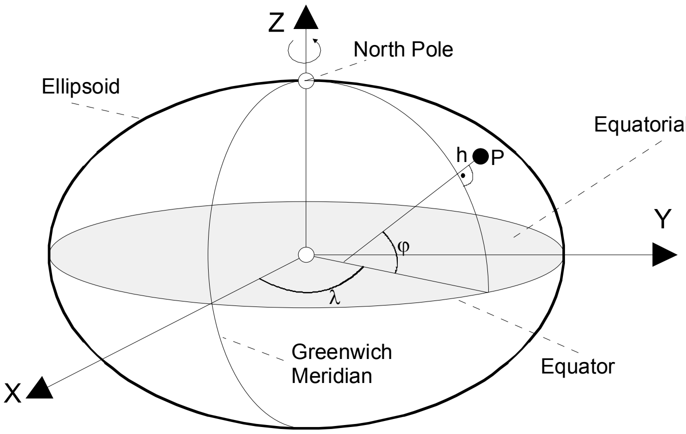


Figure 54: Illustration of the ellipsoidal co-ordinates

5.3.5 Transformation from local to worldwide reference ellipsoid

5.3.5.1 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 55) 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.

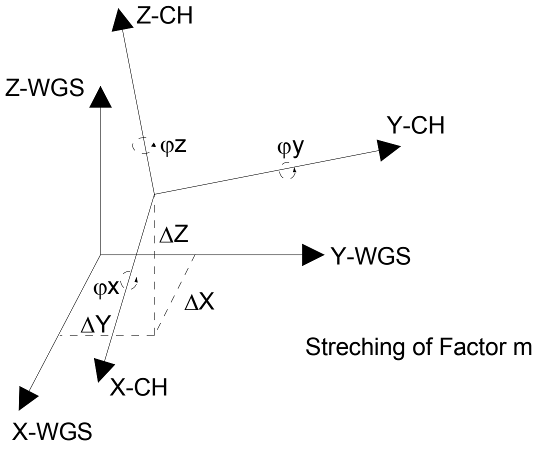


Figure 55: Geodetic datum

The following table (Table 10) shows examples of the various datum parameters. Additional values can be found under [xviii].

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 10: Datum parameters

5.3.5.2 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 [xix], or conversion can be carried out directly via the Internet [xx]. Once conversion has taken place, Cartesian co-ordinates can be transformed into ellipsoidal co-ordinates.

5.3.6 Converting Co-ordinate Systems

5.3.6.1 Converting Cartesian to ellipsoidal co-ordinates

Cartesian and ellipsoidal co-ordinates can be converted from the one representation to the other. Conversion is, however, dependent on the quadrant 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. [xxi]

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

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

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

5.3.6.2 Converting ellipsoidal to Cartesian co-ordinates

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

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

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

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

5.4 Planar regional coordinates, projection

Usually the ordnance survey depicts the position of a point P on the surface of the earth through the ellipsoid coordinates' latitude φ and longitude λ (in relation to the reference ellipsoid) and height (in relation to the ellipsoid or geoid).

Given that geoid calculations (e.g. the distance between two buildings) on an ellipsoid are numerically awkward, general survey technical practices project the ellipsoid onto a plane. This leads to planar, right-angled X and Y regional coordinates. Most maps feature a grid, which enables finding a point in the open easily. In the case of planar regional coordinates there are mappings (projections) of ellipsoid coordinates of the survey reference ellipsoid in a calculation plane. The projection of the ellipsoid in a plane is not possible without distortions. It is possible, however, to choose the projection in such as way that the distortions are kept to a minimum. Usual projection processes are cylindrical or Mercator projection or the Gauss-Krüger and UTM projection. Should position information be used in conjunction with map material, it must be remembered which reference system and which projection configuration is going to be used for making the maps.

5.4.1 Gauss-Krüger projection (Transversal Mercator Projection)

The Gauss-Krüger projection is a tangential conformal transverse Mercator projection and is only applicable to a limited area or region. An elliptical cylinder is laid around the earth's rotation ellipsoid (e.g. Bessel ellipsoid), whereby the cylinder surface touches the ellipsoid in the central meridian (an important meridian for the region to be illustrated, e.g. 9°) along its whole longitude and in the poles. The cylinder position with regard to the ellipsoid is transversal, e.g. rotated by 90° (Figure 56)). In order to keep the longitudinal and surface distortions to a minimum, 3° wide zones of the rotation ellipsoid are used. The zone width is fixed around the central meridian. Different central meridians are used depending on the region (e. g. 6°, 9°, 12°, 15°, ...).

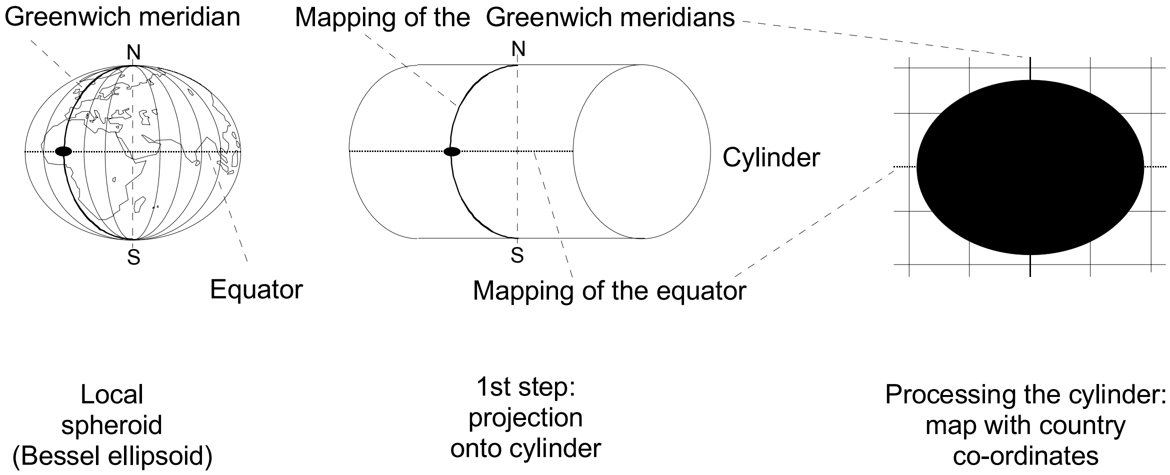


Figure 56: Gauss-Krüger projection

The values in the north-south direction are counted as the distance from the equator. In order to avoid negative values in the west-east direction the value of +500000m (Offset) is accepted for the central meridian. The central meridian's number of degrees is divided by 3 and placed in front of this value.

Example of a position:

Ellipsoid coordinates :	N:46.86154°	E 9.51280°
Gauss-Krüger (Central meridian: 9°):	N-S: 5191454	W-E: 3539097

The position is at a distance of 5191454m from the equator and 399097m from the central meridian (9°).

5.4.2 UTM projection

In contrast to the Gauss-Krüger projection the UTM (Universal Transversal Mercator) system projects almost the entire surface of the earth on 60∗20 = 1200 planes. The actual projection of the rotation ellipsoid on the transversal cylinder is carried out in accordance with the same process as in the Gauss-Krüger projection.

The UTM system is often based on the WGS84 ellipsoid. However, it only defines the projection and the coordinate system and not the reference ellipsoid and the geodesic datum.

The UTM system divides the whole world into 6° wide longitudinal zones (Figure 57). These are numbered from 1 to 60 beginning with 180° W, and ending with 180° E. If, for example zone 1 stretches from 180° W to 174° W, the central meridian of this zone 1 is situated at 177° W, zone 2 stretches from 174° W to 168°, the central meridian of this zone 2 is situated at 171° W, etc.

The central meridians for each projection zone are 3°, 9°, 15°, 21°, 27°, 33°, 39°, 45°, 51°, 57°, 63°, 69°, 75°, 81°, 87°, 93°, 99°, 105°, 111°, 117°, 123°, 129°, 135°, 141°, 147°, 153°, 159°, 165°, 171°, 177° east (E) and west (W) (longitude) (Figure 58).

In the north-south direction (to the poles) the zones are subdivided, with an exception in the 8° belt of latitude, and are identified with letters beginning with C. Only the area between 80° south to 84° north is admitted. The line from 80° south to 72° south is designated as Section C, the line from 72° south to 64° south Section D, etc. An exception to this is belt known as latitude X between 72° north and 84° north. It is 12° wide.

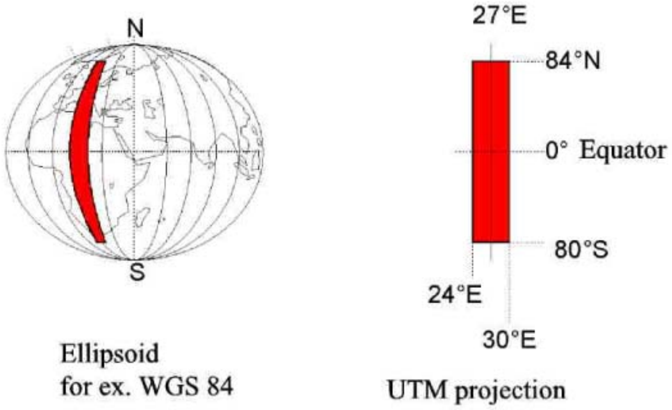


Figure 57: Principle of projecting one zone (of sixty)

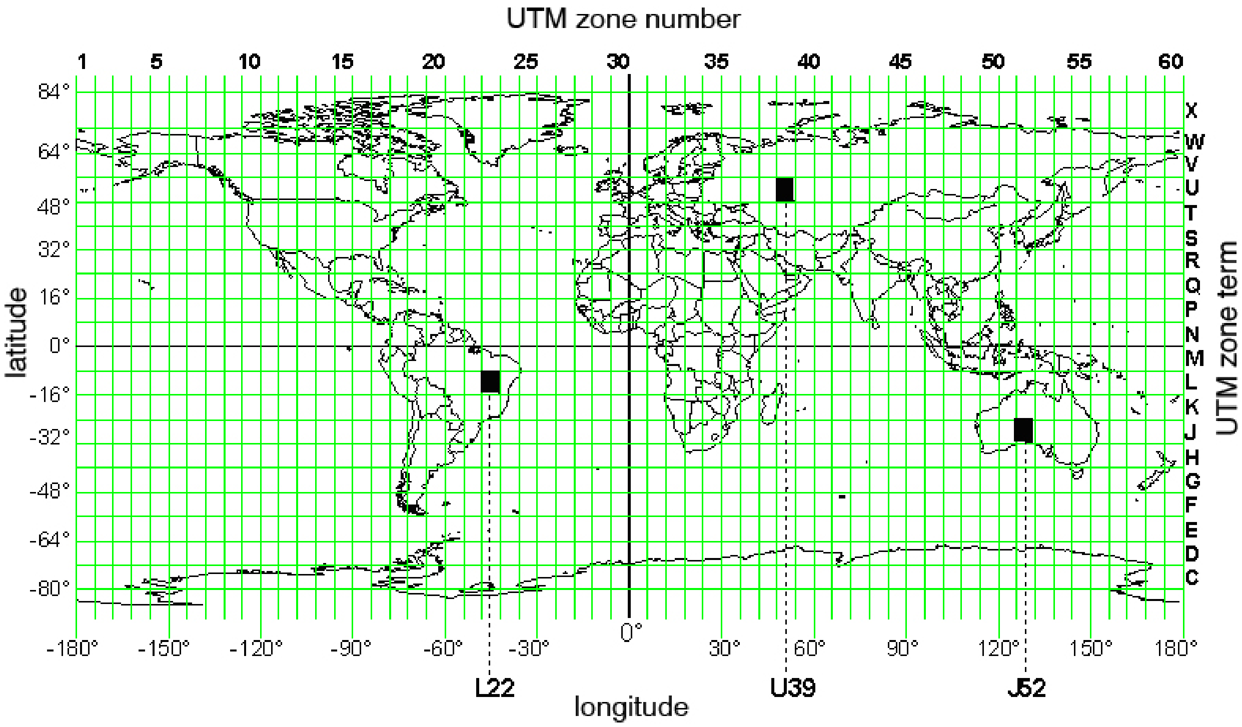


Figure 58: Designation of the zones using UTM, with examples

As is the case with Gauss-Krüger Projection, the north-south value is measured in kilometers as the distance of the point from the equator. In order to avoid negative values in the southern hemisphere, the equator is arbitrarily assigned the value of 10,000,000m.

The west-east values are the distance of the point from the central meridian, which (also as with the Gauss-Krüger Projection) is given the value of 500,000m.

An example of UTM coordinates in comparison to WGS 84 would be:

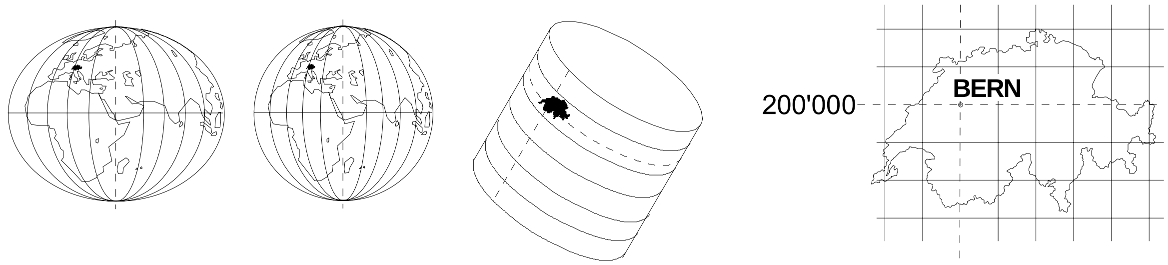
WGS 84:	N 46,86074°	E 9,51173°
UTM: 32 T	5189816 (N-S)	0539006 (W-E)

5.4.3 Swiss projection system (Conformal Double Projection)

The Bessel ellipsoid is conformally projected onto a plane in two steps, i.e. angle preserving. Initially there is conformal projection of the ellipsoid on a sphere, then the sphere is conformally projected onto a plane using an oblique cylindrical projection. This process is called double projection (Figure 59). A main point is fixed in the plane on the ellipsoid (old observatory from Bern) in the projection of the origin (with Offset: Y_{Ost} = 600,000 m and X_{Nord} = 200,000 m) of the coordinate system.

On Switzerland's map (e.g. scale 1:25000) there are two different pieces of coordinate information:

- The regional coordinates projected in the plane (X and Y in kilometers) with the accompanying grid and
- The geographical coordinates (Longitude and latitude in degrees and seconds) related to 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 59: 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 (Figure 60).

Figure 60: From satellite to position

5.4.4 Worldwide conversion of coordinates

Internet offers various possibilities for converting coordinates from one system into another [xxii].

5.4.4.1 Example: conversion of WGS-84 coordinates to CH-1903 coordinates

(From reference systems in practice, Urs Marti, Dieter Egger, Swiss Federal Office of Topography)

! **Note:** accuracy is within 1 meter!

1. Conversion of latitude and longitude:

The latitude and longitude of the WGS-84 data have to be converted into sexagesimal seconds [´´].

Example:

1. The latitude (WGS-84) of 46° 2´ 38,87´´ once converted is 165758.87´´. This integer is described as B: B = 165758.87´´.
2. The longitude (WGS-84) of 8° 43´ 49,79´´ once converted is 31429.79´´. This integer is described as L: L = 31429.79´´.

2. Calculation of auxiliary integers:

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

Example: $\Phi = -0.326979$

$\Lambda = 0.464729$

3. Calculation of 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. Calculation of 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. Calculation of the height H:

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

Example:

$\text{Height}_{\text{WGS-84}}$ = 650.60m results from the conversion: H = 600m

6 Improved GPS: DGPS, SBAS, A-GPS and HSGPS

If you would like to . . .

- Know which kinds of errors influence the accuracy of determining position
- 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
- Know how A-GPS functions

*Then **this chapter** is for you!*

6.1 Introduction

The forerunner of all GNSS systems is GPS. In fact this is so much the case that GPS is often used to refer to satellite navigation in general. In its development GPS has shown some limitations, which have required refinements and improvements in the technology. This chapter examines some of these technological enhancements to GPS, which have become standards to GNSS.

Although originally intended for military purposes, the GPS system is used today primarily for civil applications, such as surveying, navigation, positioning, measuring velocity, determining time, monitoring etc, etc, etc. GPS was not initially conceived for applications demanding high precision, security measures, or utilization in closed rooms. For this reason improvements have been implemented.

- To increase the accuracy of positioning, Differential-GPS (D-GPS) was introduced.
- To improve the accuracy of positioning and the integrity (reliability, important for security applications) SBAS (Satellite Based Augmentation System) such as EGNOS and WAAS was implemented.
- To improve the sensitivity in closed rooms, or respectively to reduce the acquisition time, Assisted-GPS (A-GPS) services were offered.
- The reception properties of GPS receivers are continually being improved and increase the sensitivity of the receivers with High Sensitivity-GPS (HSGPS).

6.2 Sources of GPS Error

The positioning accuracy of approx. 13 m for 95% of all measurements (with HDOP the accuracy is within 1.3m) discussed in the previous chapter is not sufficient for all applications. In order to achieve accuracy to within a meter or better, extra efforts are necessary. Different sources can contribute to the total error in GPS measurements. These causes and the total error are listed in Table 11. These values should be viewed as typical averages and can vary from receiver to receiver.

Error Source	Error
Ephemeris data	2.1m
Satellite clocks	2.1m
Effect of the ionosphere	4.0m
Effect of the troposphere	0.7m
Multipath reception	1.4m
Effect of the receiver	0.5m
Total RMS value	5.3m
Total RMS value (filtered, i.e. slightly averaged)	**5.0m**

Table 11:Error Source and total error

The error causes are studied in more detail below:

- **Ephemeris data**: the satellite position at the time of the signal emission is, as a general rule, only known to be accurate up to approx. 1 ... 5 m.
- **Satellite clocks:** although each satellite includes four atomic clocks, the time base contains defects. A time error of 10 ns is reached at an oscillator stability of approx. 10^{-13} per day. A time error of 10ns immediately results in a distance error of about 3 m.
- **Effect of the ionosphere:** the ionosphere is an atmospheric layer situated between 60 to 1000 km above the Earth's surface. The gas molecules in the ionosphere are heavily ionized. The ionization is mainly caused by solar radiation (only during the day!). Signals from the satellites travel through a vacuum at the speed of light. In the ionosphere the velocity of these signals slows down and therefore can no longer be viewed as constant. The level of ionization varies depending on time and location, and is strongest during the day and at the equator. If the ionization strength is known this effect can, to a certain extent, be compensated with geophysical correction models. Furthermore, given that the change in the signal velocity is frequency dependent, this can additionally be corrected by the use of dual frequency GPS receivers.
- **Effect of the troposphere:** the troposphere is the atmospheric layer located between 0... 15 km above the Earth's surface. The cause of the error here is the varying density of the gas molecules and the air humidity. The density decreases as the height increases. The increase in density or humidity retards the speed of the satellite signals. In order to correct this effect, a simple model is used which is based on the standard atmosphere (P) and temperature (T):
    - H = Height [m]
    - $T = 288.15\ \text{K} - 6.5 * 10^{-3} * h$ [K]
    - $P = 1013.25\ \text{mbar}\ (T/288.15\ \text{K})^{5,256}$ [mbar]
- **Multipath:** GPS signals can be reflected from buildings, trees, mountains etc. and make a detour before arriving at the receiver. The signal is distorted due to interference. The effect of multipath can be partially compensated by the selection of the measuring location (free of reflections), a good antenna and the measuring time (Figure 41)).

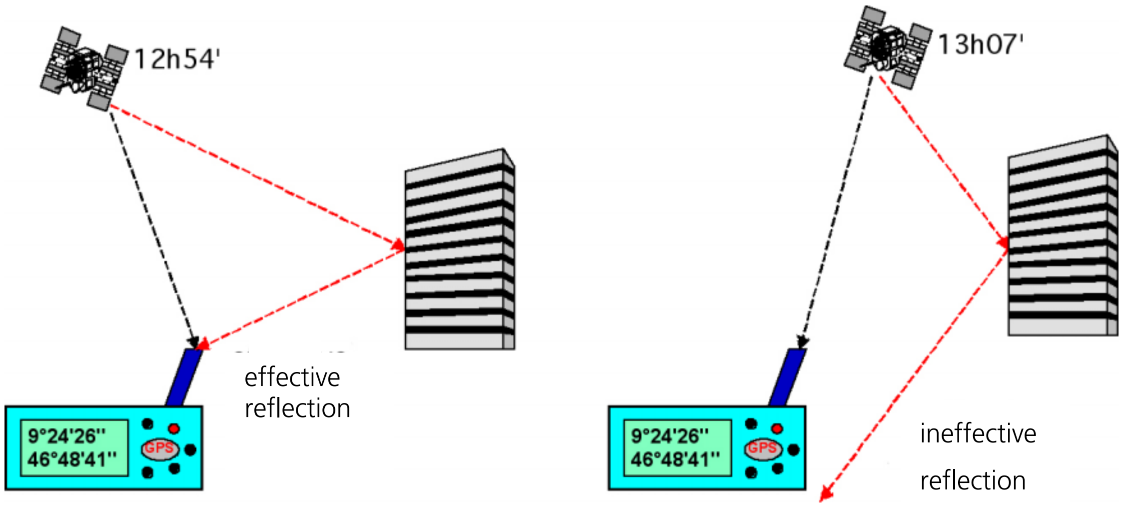


Figure 61: Effect of the time of measuring on the reflections

- **Effect of the receiver:** further errors are produced due to GPS receiver measurement noise and time delays in the receiver. Advanced technologies can be used to reduce this effect.
- **Effect of the satellite constellation, including shadowing (DOP):** this effect was discussed in detail in chapter 4.2.5.2.

6.3 Possibilities for reducing measurement error

Reducing the effect of measurement errors can considerably increase positioning accuracy. Different approaches are used for reducing the measurement error and are often combined. The processes most frequently used are:

- **Dual frequency measurement:** L1/L2 signals are used to compensate for the effect of the ionosphere. Such receivers measure the GPS L1 and L2 frequency signals. If a radio signal is transmitted through the ionosphere, it is decelerated reversely proportional to its frequency. By comparing the arrival times of both signals, the delay can be determined and thus the effect of the ionization.
- **Geophysical correction models**. This is used primarily for the compensation of the effect of the ionosphere and troposphere. Correction factors are only useful, if applied to a specified and limited area.
- **Differential GPS (DGPS):** by comparing with one or several base stations, various errors can be corrected. The evaluation of the correction data available from these stations can take place either during post processing or in Real Time (RT). Real Time solutions (RT DGPS) require data communication between the base station and the mobile receiver. DGPS employs a variety of different processes:
    - RT DGPS, normally based on the RTCM SC104 standard
        - DGPS derived from signal travel time delay measurement (Pseudorange corrections, achievable accuracy approx. 1 m)
        - DGPS derived from the phase measurement of the carrier signal (achievable accuracy approx. 1 cm)
    - Post-processing (subsequent correction and processing of the data).
- **Choice of location and of the measurement time** for improving the "visibility" or line of sight contact to the satellites (See explanation on DOP 4.2.5).

6.3.1 DGPS based on Signal Travel Time Delay measurement

The principle of DGPS based on signal travel time measurement (pseudorange or C/A code measurement) is very simple. A GPS reference station is located at a known and accurately surveyed point. The GPS reference station determines its GPS position using four or more satellites. Given that the position of the GPS reference station is exactly known, the deviation of the measured position to the actual position and more importantly the measured pseudorange to each of the individual satellites can be calculated. These variations are valid for all the GPS receivers around the GPS reference station in a range of up to 200 km. The satellite pseudoranges can thereby be used for the correction of the measured positions of other GPS receivers (Figure 62). The differences are either transmitted immediately by radio or used afterwards for correction (See post-processing, section 6.3.3) after carrying out the measurements.

It is important that the correction be based on the satellite pseudorange values and not the specific deviation in position of the GPS reference station. Deviations are based on the pseudoranges to the specific satellites, and these vary depending on position as well as which satellites are used. A correction based simply on the positional deviation of the reference base station fails to take this into account and will lead to false results.

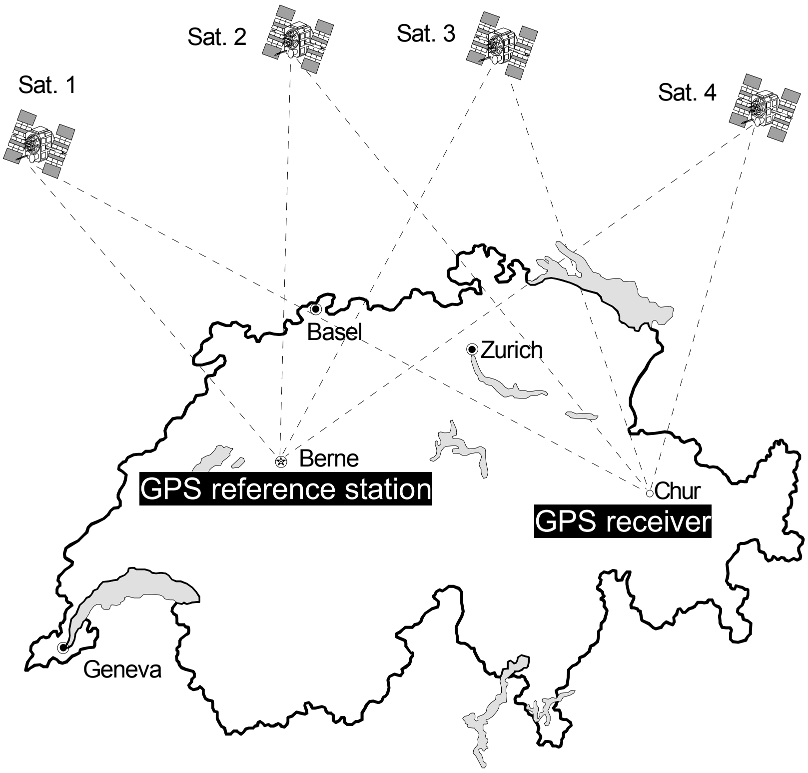


Figure 62: Principle of DGPS with a GPS base station

6.3.1.1 Detailed description of how it runs

The error compensation is carried out in three phases:

1. Determination of the correction values at the reference station
2. Transmission of the correction values from the reference station to the GPS user
3. Compensation for the determined pseudoranges to correct the calculated position of the GPS user

6.3.1.2 Definition of the correction factors

A reference station with exactly known position measures the L1 signal travel time to all visible GPS satellites (Figure 63) and uses these values to calculate its position relative to the satellites. These measured values will typically include errors. Since the real position of the reference station is known, the actual distance (nominal value) to each GPS satellite can be calculated. The difference between the nominal and the measured distances can be calculated by a simple subtraction and corresponds to a correction factor. These correction factors are different for all GPS satellites and are also applicable to GPS users within a radius of several hundred kilometers.

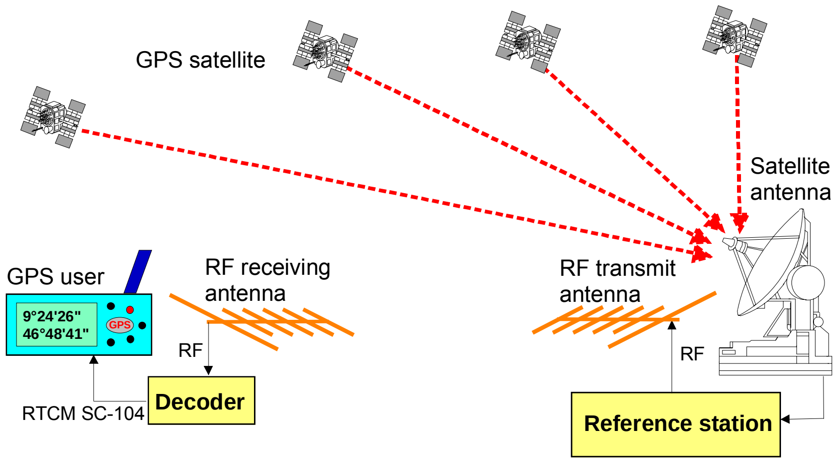


Figure 63: Determination of the correction factors

6.3.1.3 Transmission of the correction values

Given that the correction values can be used by other GPS users within a large area to compensate for the measured pseudoranges, they are immediately transmitted by using a suitable medium (telephone, radio, etc) (Figure 64).

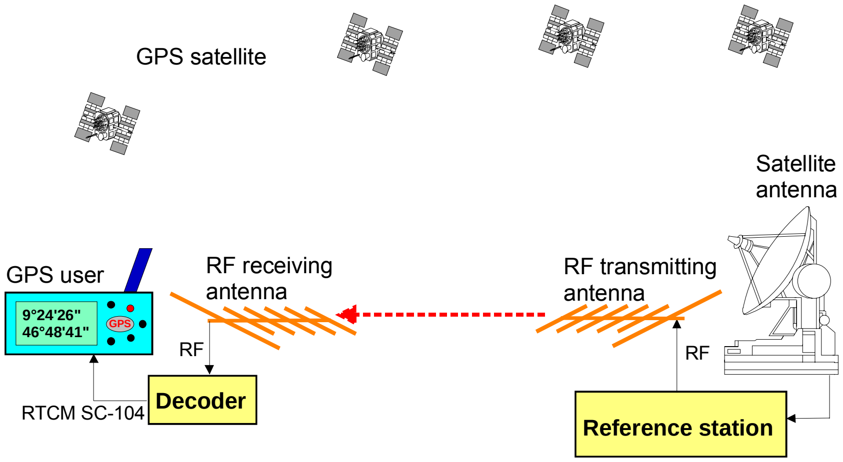


Figure 64: Transmission of the correction factors

6.3.1.4 Correction of the measured pseudo ranges

After receiving the correction values, the GPS user can compensate for the pseudoranges in order to determine the actual distance to the satellites (Figure 65). These actual distances can then be used to calculate the exact position of the user. All errors, which are not caused by receiver noise and multipath reception, can be overcome in this way.

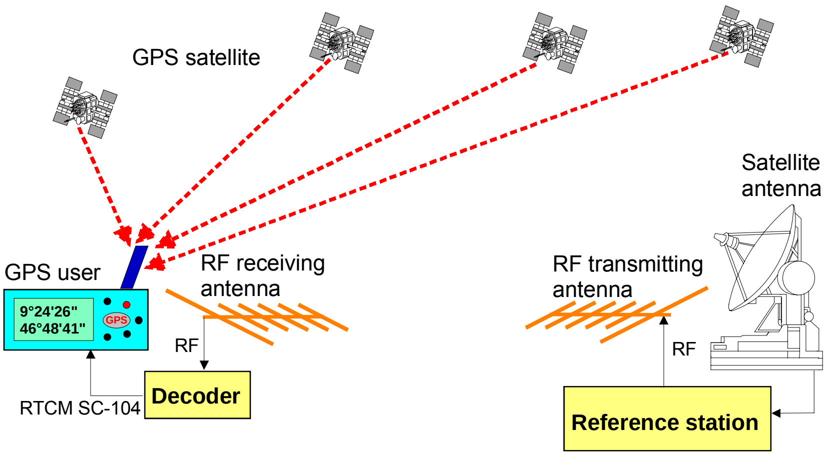


Figure 65: Correction of the measured pseudoranges

6.3.2 DGPS based on Carrier Phase measurement

The DGPS accuracy of 1 meter achieved by measuring signal travel time is not enough for some requirements such as solving survey problems. In order to obtain a precision within millimeters, the carrier-phase of the satellite signal must be evaluated.

The wavelength λ of the carrier wave is approx. 19 cm. The distance to a satellite can be determined as shown below (Figure 66).

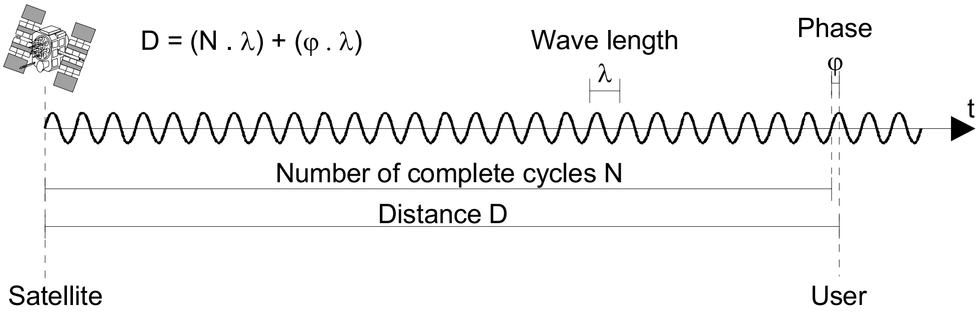


Figure 66: Principle of the phase measurement

Since N is unknown the phase measurement is ambiguous. By observing several satellites at different times and continually comparing results from user and reference station receivers (during or after the measurement), the position can be calculated using an extensive series of mathematical equations to an accuracy of a few millimeters.

6.3.3 DGPS post-processing (Signal Travel Time and Phase Measurement)

DGPS post-processing implements the determined correction factors by using appropriate software *after* carrying out field measurements. Reference data is either obtained from private reference stations or from publicly accessible server systems. The disadvantage is that problems with the field data (e.g. poor satellite reception, damaged files etc.) are sometimes not detected until after the correction factors are calculated and broadcast, necessitating a repetition of the whole process.

6.3.4 Transmitting the correction data

DGPS services collect data from reference stations and transmit it by radio to the mobile receiver. There are a variety of channels available over which to broadcast this correction data. Each of these broadcasting systems possesses individual radio-technical properties and frequency ranges which have specific advantages and disadvantages for DGPS (Table 12).

Broadcasting system	**Frequency range**	**Advantages**	**Disadvantages**	**Transmission of correction data**
Long and medium wave broadcasters (LW, MW)	100 - 600 KHz	Extensive range of transmission (1000km)	Low bit rates	RTCM SC104
Maritime radio beacon	283 - 315 KHz	Extensive range of transmission (1000km)	Low bit rates	RTCM SC104
Aviation radio beacon	255 - 415 KHz	Extensive range of transmission (1000km)	Low bit rates	RTCM SC104
Short wave broadcaster (KW)	3 – 30 MHz	Extensive range of transmission	Low bit rates, quality depends on the time and frequency	RTCM SC104
VHF and UKW	30 - 300 MHz	High bit rates, joint use of the existing infrastructure	Range of transmission limited by the quasi-optical conditions	RTCM SC104
Mobile communication/telephone networks (GSM, GPRS)	450, 900, 1800 MHz	Joint use of existing networks	Limited range of transmission, synchronization problem	RTCM SC104
GEO satellite system	1.2 – 1.5 GHz	Extensive area coverage	High investment cost	RTCM SC104 (for MSAT, Omnistar, Landstar, Starfire) RTCA DO-229C (for SBAS systems such as WAAS, EGNOS, MSAS)

Table 12: Transmission process of the differential signal (for code and phase measurement)

Many countries provide their own systems for transmitting correction data. A comprehensive description of all these systems is beyond the scope of this compendium. Some individual systems will be described below.

6.3.5 DGPS classification according to the broadcast range

The various DGPS services available are categorized according to the broadcast range of the correction signals:

- Local DGPS: Local Area Augmentation System (LAAS). These are sometimes called Ground Based Augmentation Systems (GBAS).
- Regional DGPS
- Wide Area DGPS (WADGPS) or Satellite Based Augmentation Systems (SBAS): Employ satellites to transmit DGPS correction data. In these cases not just single reference stations, but whole networks of reference stations are used.

6.3.6 Standards for the transmission of correction signals

DGPS broadcasters transmit the signal travel time and carrier phase corrections. For most GBAS and some satellite based WADGPS systems (LandStar-DGPS, MSAT, Omnistar or Starfire) the DGPS correction data is transmitted according to the RTCM SC-104 standard. Typically the receiver must be equipped with a service specific decoder in order to receive and process the data.

Satellite Based Augmentation Systems such as WAAS, EGNOS and MSAS use the RTCA DO-229 standard. Since RTCA frequencies and data formats are compatible with those of GPS, modern GNSS receivers can calculate RTCA data without the use of additional hardware, in contrast to RTCM (Figure 67).

Table 13 lists the standards used for DGPS correction signals as well as the references pertaining specifically to GNSS.

Standard		**References pertaining to GNSS**
RTCM SC 104:	Radio Technical Commission for Maritime Services, Special Committee 104	• RTCM Recommended Standards for Differential Navstar GPS Service, Version 2.0 and 2.1 • Recommended Standards for Differential GNSS Service, Version 2.2 and 2.3
RTCA:	Radio Technical Commission for Aeronautics	• DO-229C, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment.

Table 13: Standards for DGPS correction signals

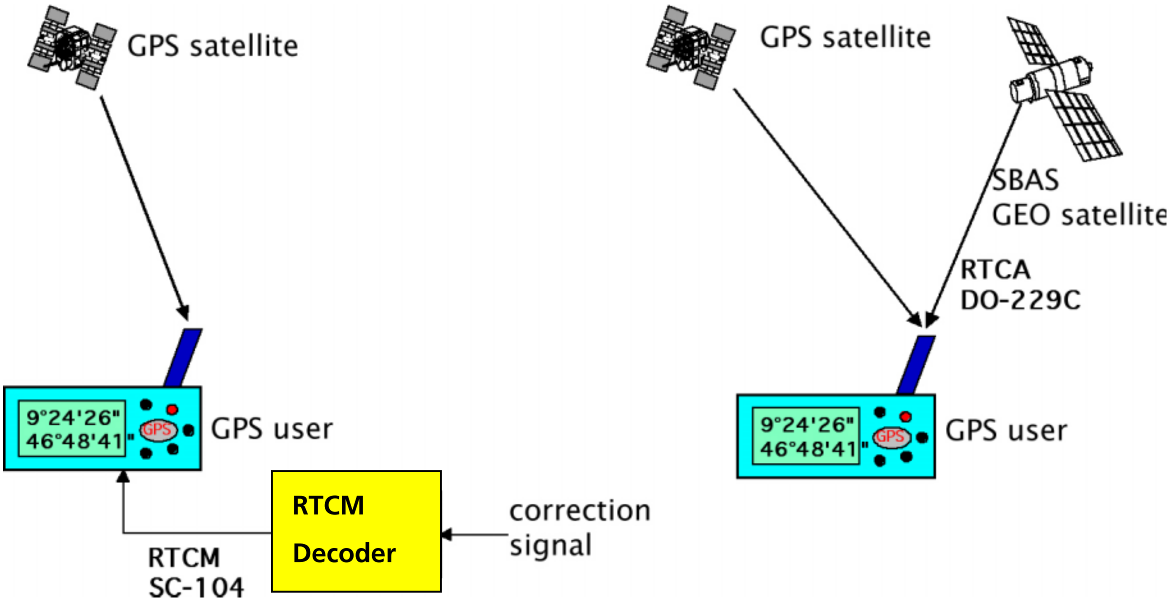
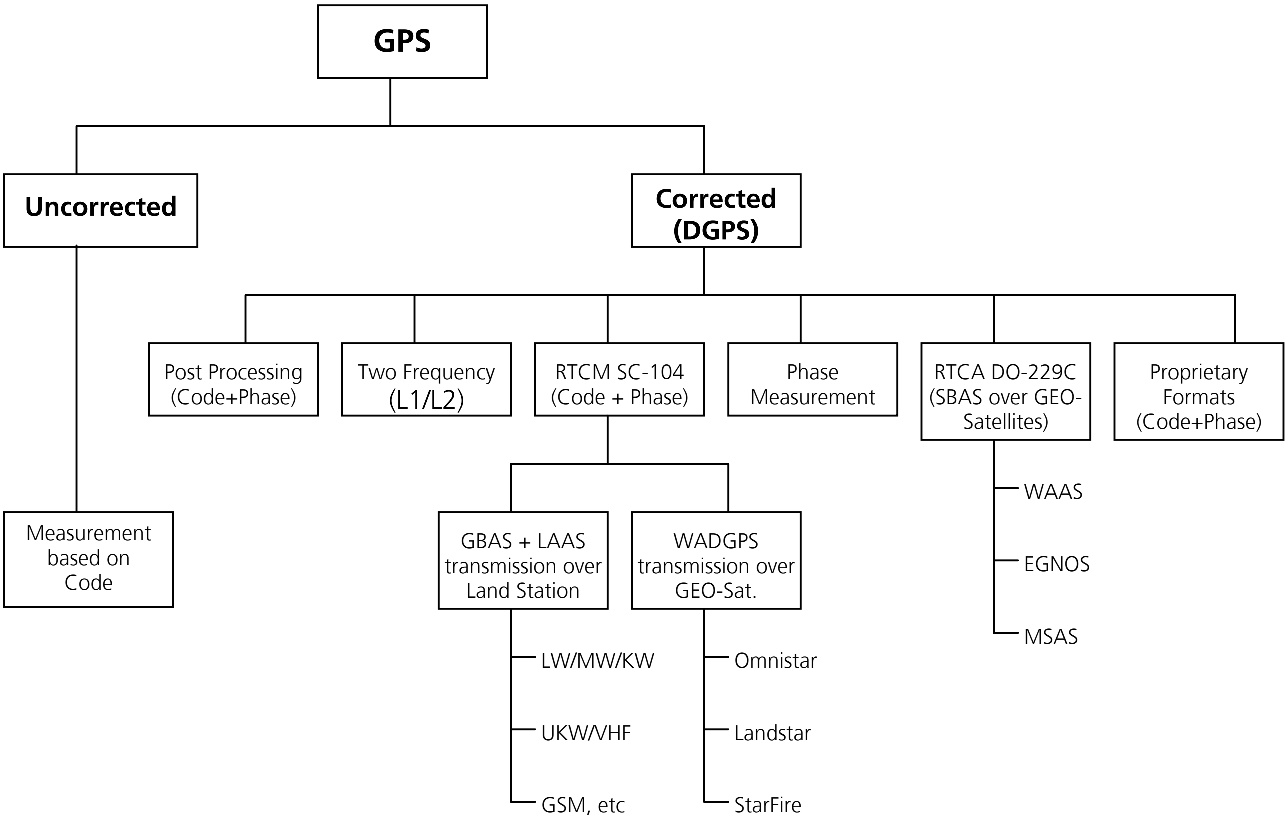


Figure 67: Comparison of DGPS systems based on RTCM and RTCA standards

6.3.7 Overview of the different correction services



6.4 DGPS services for real-time correction

All correction data is transmitted in the user receiver reception area via a suitable broadcaster (LW, KW, UKW, radio, GSM, internet, satellite communication, etc). In North America and Europe, the correction signals from multiple public DGPS services can be received. Depending on the service, an annual license fee may be required or a one-time fee is charged when purchasing the DGPS receiver.

In the following section a few selected European GBAS services will be described. Subsequently the satellite-based DGPS services will be discussed in detail.

6.4.1 GBAS Services

Worldwide there are far too many ground-based DGPS services, also known as Ground Based Augmentation Services (GBAS), to describe them all in detail here. In many countries there are multiple systems offered. The following list describes a few GBAS services available in Europe.

6.4.2 European GBAS Services

- **SAPOS:** (German Surveying and Mapping Administration Satellite Positioning Service) is a DGPS service in permanent operation. This service is available in all of Germany. The basis of the system is a network of GPS reference stations. For real-time correction values the data is transmitted using UKW radio, longwave, GSM and their own 2-meter band (VHF) frequencies. UKW radio transmitters broadcast the correction data signals in RASANT (Radio Aided Satellite Navigation Technique) format. This is a conversion of RTCM 2.0 for data transmission into the Radio Data System (RDS) format used by UKW sound broadcasting. SAPOS includes four services with different features and accuracies:
    - SAPOS EPS: Real-Time Positioning Service
    - SAPOS HEPS: High-Precision Real-Time Positioning Service
    - SAPOS GPPS: Geodetic Precision Positioning Service
    - SAPOS GHPS: Geodetic High-Precision Positioning Service
- **ALF:** (Accurate Positioning by Low Frequency) broadcasts the correction values with an output of 50 kW from Mainflingen, Germany (near Frankfurt). The longwave broadcaster DCF42 (LW, 123.7 kHz) transmits the correction values over an area of 600–1000 km. This upper sideband (USB) is phase-modulated (Bi-Phase-Shift-Keying BPSK). The German Federal Office for Cartography and Geodesy, in cooperation with the German Telecom service (DTAG), provides the service. When buying the required decoder, the user pays a one-time fee. Due to longwave propagation patterns the correction data can be received despite shadowing.
- **AMDS:** (Amplitude Modulated Data System) is used for digital transmission over medium and longwave frequencies using existing radio broadcasters. The data is phase-modulated and transmitted over an area of 600 – 1000 km.
- **Swipos-NAV:** (Swiss Positioning Service) distributes correction data using FM-RDS or GSM. The Radio Data System RDS is a European standard for the distribution of digital data via the UKW broadcasting network (FM, 87-108 MHz). RDS was developed in order to provide travelers with traffic information over UKW. The RDS data is modulated at a frequency of 57 kHz on the FM carrier. The user requires an RDS decoder in order to extract the DGPS correction values. To guarantee good reception, there should generally be line-of-sight contact with a UKW broadcaster. Users of this service can either pay an annual subscription or a one-time fee.
- **Radio Beacons:** radio beacons are navigation installations distributed worldwide primarily along the coasts. DGPS correction signals are usually transmitted along a frequency of approximately 300kHz. The signal bit rate varies depending on the broadcaster between 100 and 200 bit per second.

6.5 Wide Area DGPS (WADGPS)

6.5.1 Satellite Based Augmentation Systems, SBAS (WAAS, EGNOS)

6.5.1.1 Introduction

Satellite Based Augmentation Systems (SBAS) are used to enhance the GPS, GLONASS and GALILEO (once it is operational) functions. Correction and integrity data for GPS or GLONASS is broadcast from geostationary satellites over the GNSS frequency.

6.5.1.2 The most important SBAS functions

SBAS is a considerable improvement compared to GPS because the positioning accuracy and the reliability of the positioning information is greater. SBAS, in contrast to GPS, delivers additional signals broadcast from different geostationary satellites.

- **Increased positioning accuracy using correction data:** SBAS provides differential correction data with which the GNSS positioning accuracy is improved. First of all the ionospheric error, which arises due to the signal delays in the ionosphere, has to be corrected. The ionospheric error varies with the time of day and is different from region to region. To ensure that the data is continentally valid, it is necessary to operate a complicated network of earth stations in order to be able to calculate the ionospheric error. In addition to the ionospheric values, SBAS passes on correction information concerning the satellite position location (Ephemeris) and time measurement.
- **Increased integrity and security:** SBAS monitors each GNSS satellite and notifies the user of a satellite error or breakdown in a quick advance warning time of 6s. This yes/no information is only transmitted if the quality of the received signals remains below specific limits.
- **Increased availability through the broadcasting of navigation information:** SBAS geostationary satellites emit signals, which are similar to the GNSS signals although missing the accurate time data. A GNSS receiver can interpret position from these signals using a procedure known as "pseudoranging".

6.5.1.3 Overview of existing and planned systems

Although all Satellite Based Augmentation Systems (SBAS) include larger regions (e.g. Europe) it must be ensured that they are compatible with each other (interoperability) and that the SBAS providers cooperate with each other and agree on their approach. Compatibility is guaranteed by using the RTCA DO-229C standard. At the current time, the SBAS systems identified for the areas below are currently in operation or development and are (or will be) compatible (Figure 68):

- **North America (WAAS, Wide Area Augmentation System):** the US Federal Aviation Administration (FAA) is leading the development of the Wide Area Augmentation System (WAAS), which covers most of the continental United States and large parts of Alaska and Canada. WAAS operates over the satellites POR and AOR-W. These satellites should become active during 2007/2008. The uninterrupted continuation of this service will be achieved through two new satellites situated at 133°W and 107°W. It is planned to extend the service into Canada through the augmentation of WAAS with a Canadian "CWAAS" system.
- **Europe (EGNOS, European Geostationary Overlay Service):** the European group of three comprising ESA, the European Union and EUROCONTROL, is developing EGNOS, the European Geostationary Navigation Overlay Service. EGNOS is intended for the region of the European Civil Aviation Conference (ECAC). As of June 2006 EGNOS was not yet fully approved for operation for high security applications (e.g. aviation). The definitive release of the system is scheduled for 2007/2008. The current transmission status of the EGNOS satellites can be viewed under [xxiii].
- **Japan (MSAS, Multifunctional Satellite Based Augmentation System):** the Japanese Office for Civil Aviation is developing the MTSAT based Augmentation System (MSAS) that is intended to cover the Air Traffic Control Airspace associated with Japan.

- **India (GAGAN, GPS and GEO Augmented Navigation):** the Indian Space Research Organization (ISRO) is trying to develop a system, which is compatible with the other SBAS systems. This is to begin with the launch of the GSAT-4 satellite, planned for 2007. This is planned to be a preparation for an independent GNSS system for India to be known as the Indian Regional Navigational Satellite System (IRNSS).
- **China (Beidou):** Beidou involves three geostationary satellites (140°E, 110.5°E and 80°E) belonging to the Chinese government and is foreseen as a regional expansion system for the proposed Chinese satellite navigation system COMPASS. The definitive timeframe for the activation of this system remains unclear.

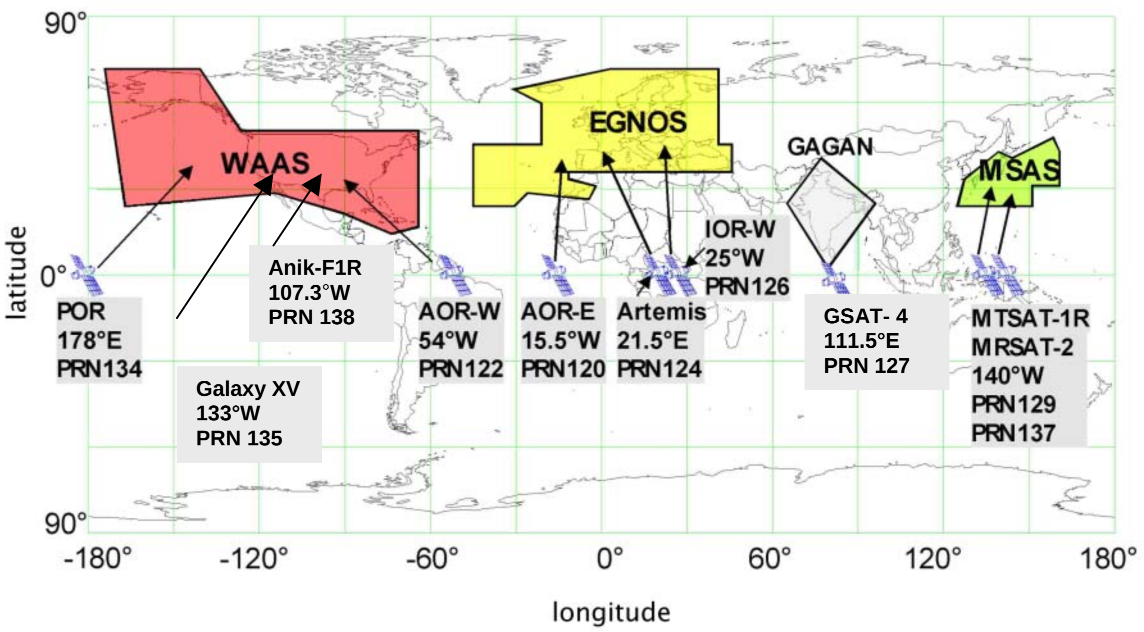


Figure 68: Position and provision of WAAS, EGNOS, GAGAN and MSAS

The geostationary satellites (Table 14) broadcast their signals from an altitude of approx. 36,000 km above the equator in the direction of the area of use. The Pseudo Random Number (PRN) for each satellite has been allocated. The broadcasting frequency of the signals is the same as GPS (L1, 1575.42 MHz).

Service	Satellite description	Position	PRN
WAAS	Inmarsat 3F3 POR (Pacific Ocean Region)	178° E	134
WAAS	Inmarsat 3F4 AOR-W (Atlantic Ocean Region West)	54° W	122
WAAS	Intelsat Galaxy XV	133° W	135
WAAS	TeleSat Anik F1R	107.3° W	138
EGNOS	Inmarsat 3F2 AOR-E (Atlantic Ocean Region East)	15.5° W	120
EGNOS	Artemis	21.5° E	124
EGNOS	Inmarsat 3F5 IOR-W (Indian Ocean Region West)	25° E	126
GAGAN	GSAT-4	111.5° E	127
MSAS	MTSAT-1R	140° E	129
MSAS	MTSAT-2	145° E	137

Table 14: The GEO satellites used (or to be used) with WAAS, EGNOS and MSAS

6.5.1.4 System description

The complex ground segment is composed of several reference base-stations, ground control centers and 2 to 3 satellite earth stations (Figure 69). Each system uses its own designation for its stations. Table 15 below compares the designations.

General description	EGNOS designation	WAAS designation	MSAS designation
Reference Base Station	RIMS: Reference and Integrity Monitoring Station	WRS: Wide Area Base station	GMS: Ground Monitor Station
Control Center	MCC: Mission Control Center	WMS: WAAS Master Station	MCS: Master Control Station
Satellite Ground Station	NLES: Navigation Land Earth Station	GES: Ground Earth Station	NES/GES: Navigation Earth Station/Ground Earth Station

Table 15: Designation of the SBAS stations

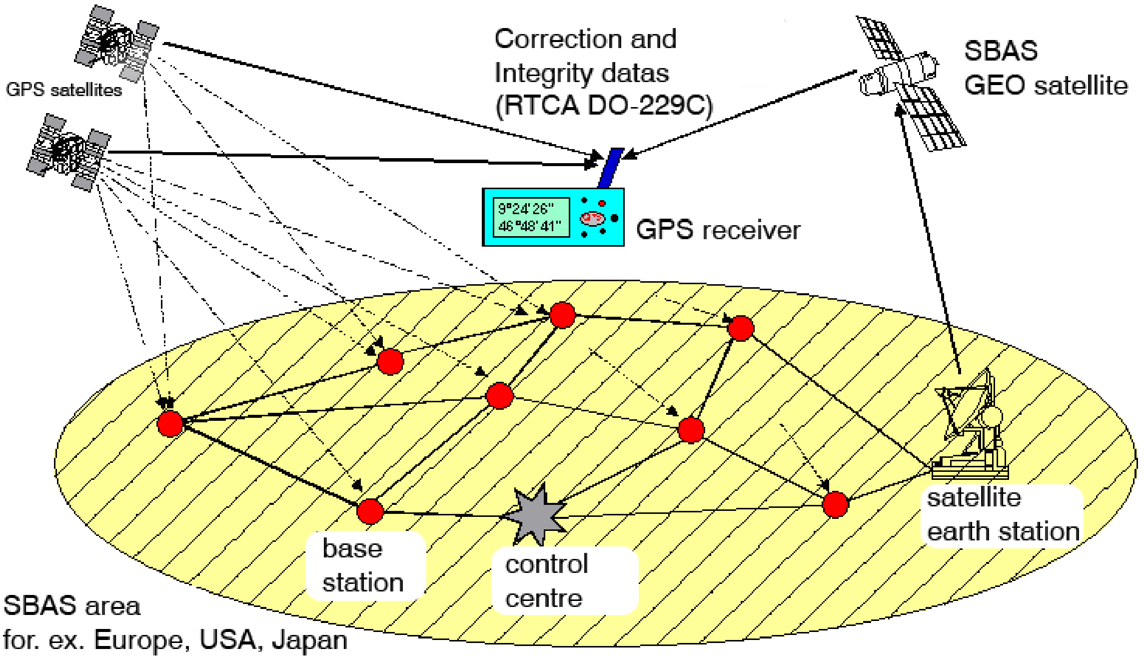


Figure 69: Principle of all Satellite Based Augmentation Systems SBAS

- **Reference Station:** in the SBAS area there are several reference base stations, which are networked to each other. The base stations receive the GNSS signals. They are exactly surveyed with regard to their position. Each base station determines the deviation between the actual and calculated positions relative to the satellites (the pseudorange). This data is then transmitted to a control center.
- **Control Center:** the control centers carry out the evaluation of the correction data from the reference base stations, determine the accuracy of all GNSS signals received by each base station, detect inaccuracies, possibly caused by turbulence in the ionosphere, and monitor the integrity of the GNSS system. Data concerning the variations are then integrated into a signal and transmitted via distributed satellite earth stations.
- **Satellite Ground Station:** these stations broadcast signals to the different geostationary satellites.

- **GEO satellites:** the SBAS GEO (geostationary) satellites receive the signals from the satellite ground stations and broadcast them to the GNSS users. Unlike the GNSS satellites, these GEO satellites do not have onboard signal generators but rather are equipped with transponders, which relay the signals processed on the ground and transmitted to them. The signals are transmitted to earth on the GNSS-L1-frequency (1575.42MHz). The SBAS signals are received and processed by suitably equipped GNSS receivers.

6.5.2 Satellite DGPS services using RTCM SC-104

Several geostationary satellites continuously broadcast correction data worldwide. Below are listed some of these services. These services use the RTCM SC-104 standard and require a special decoder.

- **MSAT:** developed by the National Research Council of Canada, this service broadcasts the Canada-Wide DGPS (CDGPS) signals using two geostationary satellites.
- **Omnistar** (Fugro Group) and **LandStar-DGPS,** (Thales Company), independently broadcast correction data via 6 GEO satellites (Figure 70). The services must be paid for and the user must have access to a special receiver / decoder for using the service. Omnistar and Landstar broadcast their information in L-band (1-2 GHz) to earth. Base stations are distributed worldwide. The geostationary satellites are located in the central latitude deep over the horizon (10° ... 30°). Line-of-sight contact is required in order to establish radio contact.

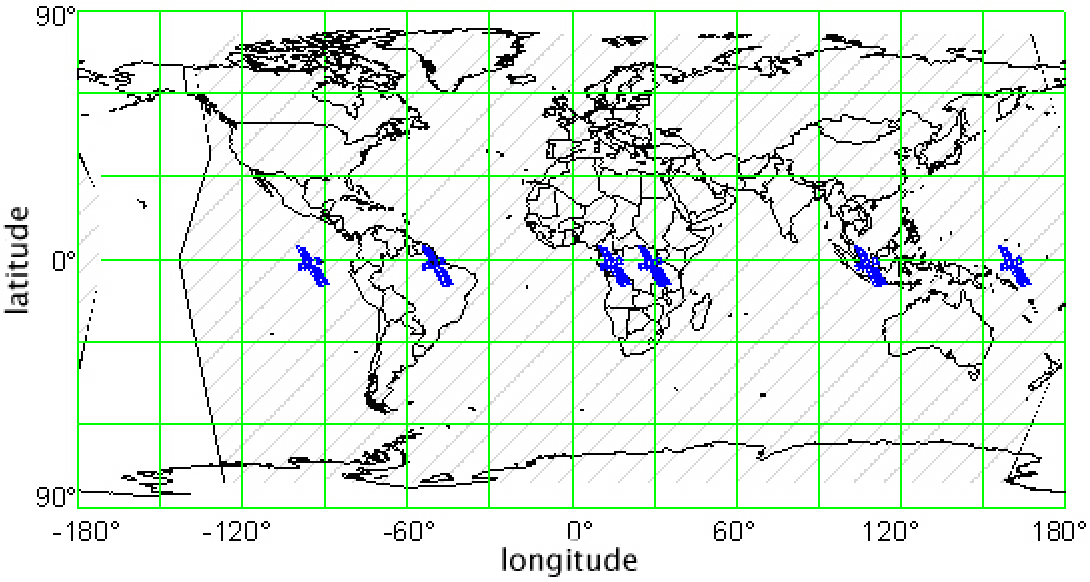


Figure 70: LandStar-DGPS and Omnistar illumination zone

- **Starfire** Property of NavCom Technology, Inc., broadcasts correction data via 3 Inmarsat GEO satellites. The service has to be paid for and the user must have access to a special receiver / decoder in order to use the service. Starfire broadcasts its information in L-band (1-2 GHz) to earth. The respective base stations are distributed throughout the whole world. The service is available worldwide over the range of ± 76° latitude.

6.6 Achievable accuracy with DGPS and SBAS

Table 16 shows typically achievable positioning accuracy with and without DGPS/SBAS.

Error cause and type	**Error without DGPS/SBAS**	**Error with DGPS/SBAS**
Ephemeris data	2.1m	0.1m
Satellite clocks	2.1m	0.1m
Effect of the ionosphere	4.0m	0.2m
Effect of the troposphere	0.7m	0.2m
Multipath reception	1.4m	1.4m
Effect of the receiver	0.5m	0.5m
Total RMS value	5.3m	1.5m
Total RMS value (filtered i.e. slightly averaged)	5.0m	1.3m
Horizontal error (1-Sigma (68%) HDOP=1.3)	6.5m	1.7m
Horizontal error (2-Sigma (95%) HDOP=1.3)	**13.0m**	**3.4m**

Table 16: Positioning accuracy without and with DGPS/SBAS

6.7 Assisted-GPS (A-GPS)

6.7.1 The principle of A-GPS

It can be assumed that devices for Location Based Services (LBS, see 9.2.1) aren't always in operation. This is especially so in cases where localization is achieved with GNSS because battery operation is prevented during longer stationary periods in order to minimize power consumption. Because the GNSS device is only infrequently in operation it is probable that no information is available regarding satellite position. After being inactive for 2 or more hours the orbital data of the satellites must first be downloaded in order to start up. A GNSS receiver normally requires at least 18-36 seconds in order to obtain the orbital data and calculate the first position. Under difficult reception conditions (e.g. in urban areas where high buildings block direct sight to the sky) the calculation of the first position can require minutes for completion (if at all).

In the absence of the orbital data the GNSS receivers must carry out a complete search procedure in order to find the available satellites, download the data and calculate the position. Searching for the GPS satellites (for example) in the Code-Frequency-Level is very time consuming. The correlation time normally requires at least 1 ms (1 C/A Code Period) per position in the Code-Frequency-Level. Should the frequency range be broken into 50 steps (i.e. the frequency interval amounts to (2 x 6000 / 50 Hz = 240 Hz) then there can be as many as 1023 x 50 = 51,150 positions (bins) to be searched for (this represents 51 seconds). See also section 6.8.

This problem can be remedied by making the satellite orbital data and other GNSS information available through other communications channels, for example via GSM, GPRS, CDMA or UMTS. This is referred to as Aiding and is employed by Assisted-GPS. Assisted-GPS (or A-GPS) is a function or service that uses Aiding-Data in order to expedite the position calculation. The GNSS receiver obtains Aiding-Data over a mobile communications network (perhaps directly over the internet). The Aiding-Data includes information over such things as:

- Satellite Constellation (Almanac)
- Precise Orbital Data (Ephemeris, Orbits)
- Time Information
- Doppler Frequency and Frequency-Offset (Error) of the GNSS Receiver

With the availability of this help information the GNSS receiver can very quickly calculate position, even under poor conditions. Depending on the complexity and completeness of the help information the reduction of the start-up time can be significant. The start-up time remains dependant on the strength of the GNSS-Signal. It is generally true, however, that the more help information available, the faster the start-up time.

A mobile transmitter station with integrated GNSS device still requires sight to at least four satellites. To use A-GPS the GNSS receivers require an interface through which to receive the Aiding-Data.

The greatest time saving occurs through eliminating the reception time for the orbital data. In addition to this, the search area can be limited when the Doppler Frequency and Frequency Offset of the GNSS receiver is known (Figure 71). This causes the Signal Acquisition to be accelerated which saves additional time.

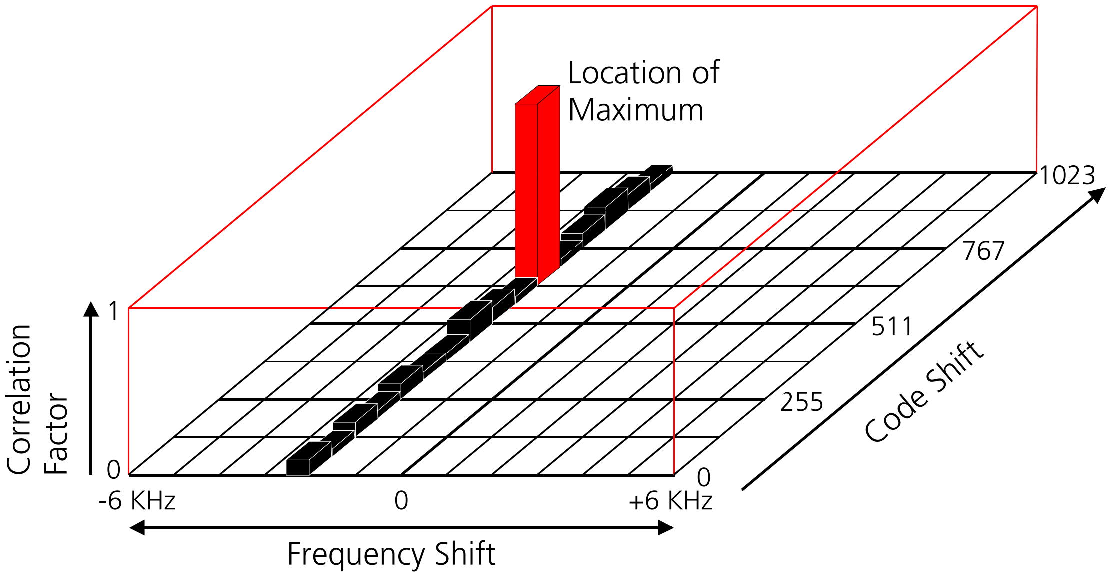


Figure 71: Acceleration of the search procedure with A-GPS by reducing the search area

Two different techniques are employed to use the Help Information:

- With the **Online Principle** the Aiding-Data are directly downloaded from a server as needed in real-time. This information is only valid for a limited time. (e.g. AssistNow® Online by u-blox AG)

- With the **Offline Principle** the Aiding-Data (generally predetermined Ephemeris or Almanac information) is downloaded from a server and stored in the GNSS device prior to the application. The data can remain valid for up to several days. As needed the stored data can be utilized in order to accelerate the start-up. (e.g. AssistNow® Offline by u-blox AG)

The help information is collected from a network of GNSS-Reference Stations (GNSS Reference Network) distributed worldwide.

A typical A-GPS system, as illustrated in the below block diagram (Figure 72), consists of a global reference network of GNSS receivers, a central server that distributes Aiding-Data, and A-GPS capable receivers (the GNSS end devices). The GNSS receivers of the global reference network receive the relevant satellite information and forward it to the server. The server calculates the Aiding-Data and transmits it (over a mobile communications network or over the Internet) upon request to the GNSS end devices, which in turn can more quickly calculate their first position.

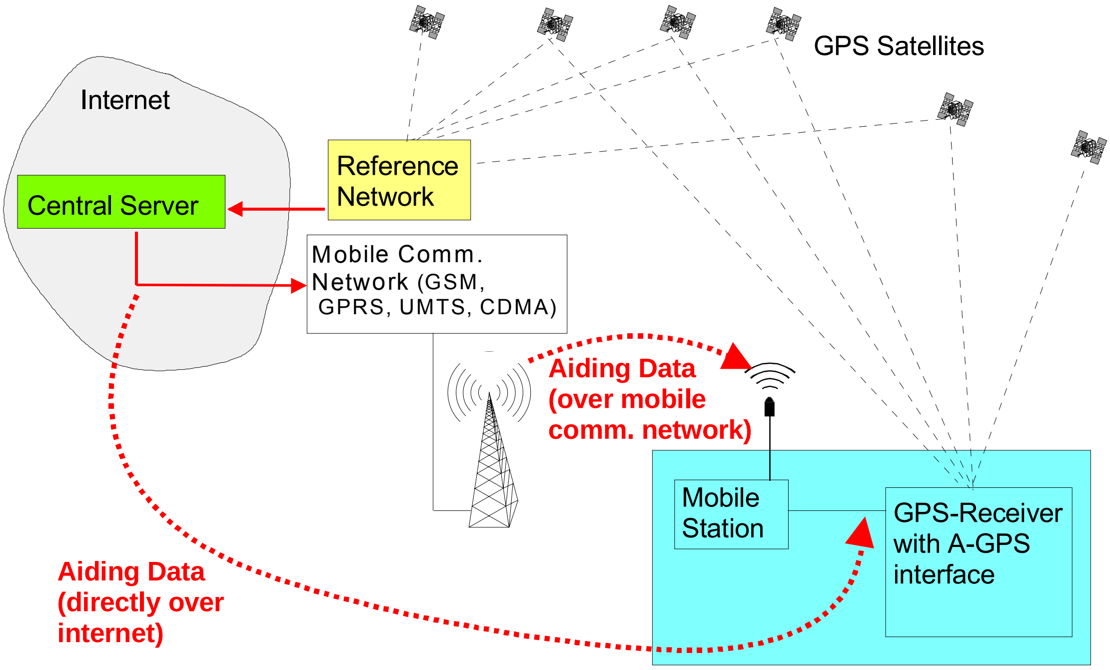


Figure 72: Assisted-GPS system

6.7.2 A-GPS with Online Aiding Data (Real-time A-GPS)

With the Online or Realtime Principle the Aiding Data are directly downloaded from the server as needed and are only valid for a short time. The disadvantage of this principle is the relatively slow connection time (GPRS, for example, requires up to 30 seconds) or inadequate availability of Internet Access Points.

6.7.3 A-GPS with Offline Aiding Data (Predicted Orbits)

A-GPS with Offline Aiding Data is a system providing the GNSS receiver with predetermined orbital data (Predicted Orbits). The receiver stores this information, and the connection to the server is terminated. The next time the GNSS receiver starts up the stored information is used to determine the current orbital information for navigation. Consequently it is no longer necessary to wait until all of this information has been downloaded from the satellites and the receiver can immediately begin navigating. Depending on the provider the Aiding Data can be valid for up to 10 days, although it should be considered that the resulting positional accuracy decreases with time.

6.7.4 Reference Network

Predetermining the orbitals with which to supply Real-time A-GPS Data requires an extensive and worldwide network of monitoring stations, which continually and accurately monitor satellite movements. A high performance server uses this data to predict satellite movements over the next days. An example of such a network is the one developed by the International GNSS-Service (IGS, or International GPS-Service [xxiv]), which worldwide operates a permanent network (Figure 73).

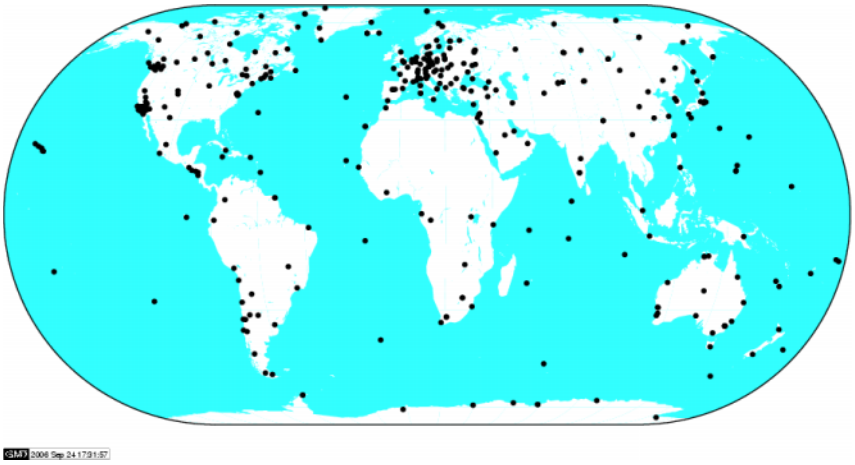


Figure 73: IGS reference stations (as of October 2006) with approx. 340 active stations

6.8 High Sensitivity GPS (HSGPS)

While certain applications, such as calling emergency numbers or Location Based Services, require clear reception in buildings or in urban canyons, the reception performance of GNSS-Receivers is being continually improved. The primary focuses of these efforts are:

- Increased Signal Sensitivity
- Quicker acquisition upon activation of the receiver (time to first fix, TTFF)
- Reduced sensitivity to interference (e.g. multipath interference, or electromagnetic interference EMC)

Various strategies are being employed by different manufacturers in order to achieve improvements. The most important of these are discussed in this chapter including:

- Improved Oscillator Stability
- Antennas
- Noise Figure considerations
- Increasing the correlators and the correlation time

6.8.1 Improved Oscillator Stability

The development and use of increasingly stable oscillators is an attempt to reduce or compensate for the temperature dependence of quartz in order to decrease signal acquisition time in the required frequency areas. This mostly involves the employment of temperature compensated crystal oscillators (TCXO).

Additionally, studies have shown [**XXV**] that normal quartz oscillators can produce micro variations in frequency (several 10^{-9}Hz). The causes of these frequency changes are generally structural impurity of the quartz crystal. On the basis of these sudden frequency shifts the acquisition time is increased because the search in the Frequency-Code-Level during the correlation process is disrupted. Developing quartz oscillators with reduced tendencies to micro variations can reduce this disturbance.

6.8.2 Antennas

Antennas can be made to be less sensitive to disturbances and to selectively receive GNSS frequencies. The disadvantage of this performance improvement is an increase in size. This contradicts the general trend towards miniaturization of mobile stations.

6.8.3 Noise Figure Considerations

The Noise Figure (NF) is a measure that indicates to what extent the signal to noise ratio of an incoming signal is decreased by the additional noise of the receiver. Minimizing the noise and maximizing the amplification at the first amplification stage (LNA), minimally improves the receiver sensitivity. As is the case with every receiver the first stage amplification determines the noise characteristics for the entire receiver.

This is demonstrated in the below equation as well as in the simplified block diagram (Figure 74) with the LNA and the combined subsequent stages (SS):

$$NF_{Total} = NF_{LNA} + \frac{NF_{SS}}{G_{LNA}}$$

NF: Noise Figure (dB) of the Stage

G: Gain of the Stage

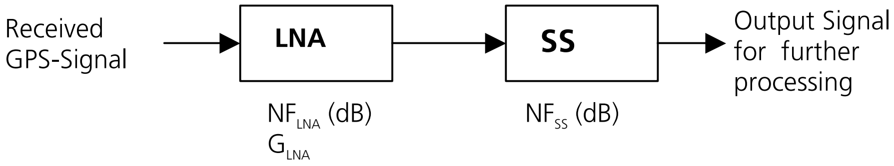


Figure 74: Block Diagram of input stages

With typical noise figures for the first and subsequent amplification stages- of 20 dB and 1.6 dB respectively, only marginal improvements are possible with new LNA developments [xxvi]. Further advancement in this area appears to be unlikely.

6.8.4 Correlators and Correlation Time

The spectral power density of the received GNSS signals is approx. 16 dB below the power density of the thermal background noise (see Figure 16). The demodulation and de-spreading of the received GNSS signals creates a system gain G_G of 43dB (see Figure 24).

Increasing the correlation time (Integration Time or Dwell-Time) improves the sensitivity of a GNSS module. The longer a correlator remains at a specific code-frequency level, the lower the required strength of the GNSS signal at the antenna. If the correlation time is increased by a factor of k, then there will be an increase G_R in the separation to the thermal background noise of:

$G_R = \log_{10} (k)$

Doubling the Correlation time results in an increase of the signal-background noise separation of 3 dB. In practice an increase in the correlation time of 20 ms is not a problem. When the value of the transmitted data bits is known this time can be additionally increased. Otherwise it is possible through a non-coherent integration to increase the correlation time to over 1 second, however, this procedure results in a one-time loss of several dB.

In order to increase the acquisition sensitivity the number of implemented correlators is significantly increased.

Modern GNSS receivers typically possess a sensitivity of approximately –160 dBm. Given that the GPS operator (US Department of Defense) guarantees signal strength of –130 dBm, GNSS receivers can therefore function in buildings that weaken the signal by up to 30dB.

6.9 GNSS-Repeater or Reradiation Antenna

A GNSS-Repeater (also known as a Reradiation Antenna or Transceiver) receives GNSS-Signals from visible satellites through an externally situated antenna, amplifies the signals and transmits them to another location (e.g. into a building). They require no direct connection to the GNSS device. The reception antenna is installed outdoors in a location favorable for receiving satellite signals. The GNSS-Repeater (Figure 75) consists of:

- External Antenna (Reception Antenna)
- Internal Antenna (Transmission Antenna)
- Electrical adapter
- Amplifier
- Cable

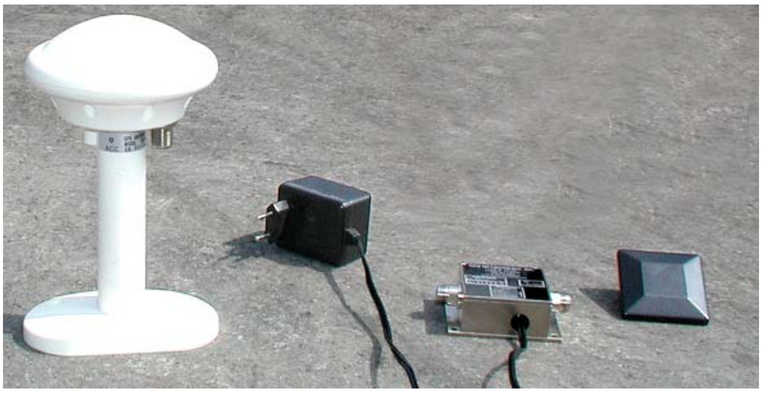


Figure 75: GNSS Repeater (external antenna, electrical adapter and power cord, amplifier and internal antenna)

6.10 Pseudolites for indoor applications

A Pseudolite (short form for pseudo satellite) is a ground-based transmitter, which functions like a GNSS satellite. Pseudolites are often used in aviation to support aircraft landing approaches. This procedure is not commonly used for indoor applications because the necessary components are relatively expensive.

7 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 GNSS receivers
- know what an active antenna is
- know whether GNSS receivers have a synchronized timing pulse

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

7.1 Introduction

GNSS receivers require different signals in order to function (Figure 76). These variables are broadcast after position and time have been successfully calculated. 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.

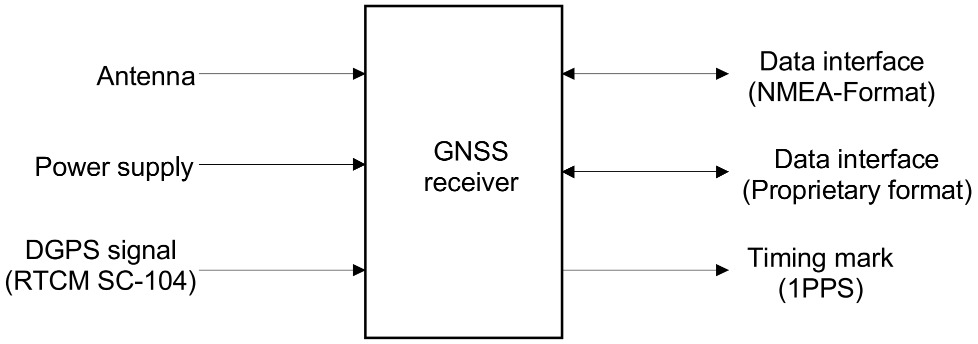


Figure 76: Block diagram of a GNSS receiver with interfaces

7.2 Data interfaces

7.2.1 The NMEA-0183 data interface

In order to relay computed GNSS variables such as position, velocity, course etc. to a peripheral (e.g. computer, screen, transceiver), GNSS 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 standardized 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 GNSS modules to relay GNSS information [xxvii]:

1. GGA (GPS Fix Data, fixed data for the Global Positioning System)
2. GGL (Geographic Position – Latitude/Longitude)
3. GSA (GPS 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)

7.2.1.1 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.

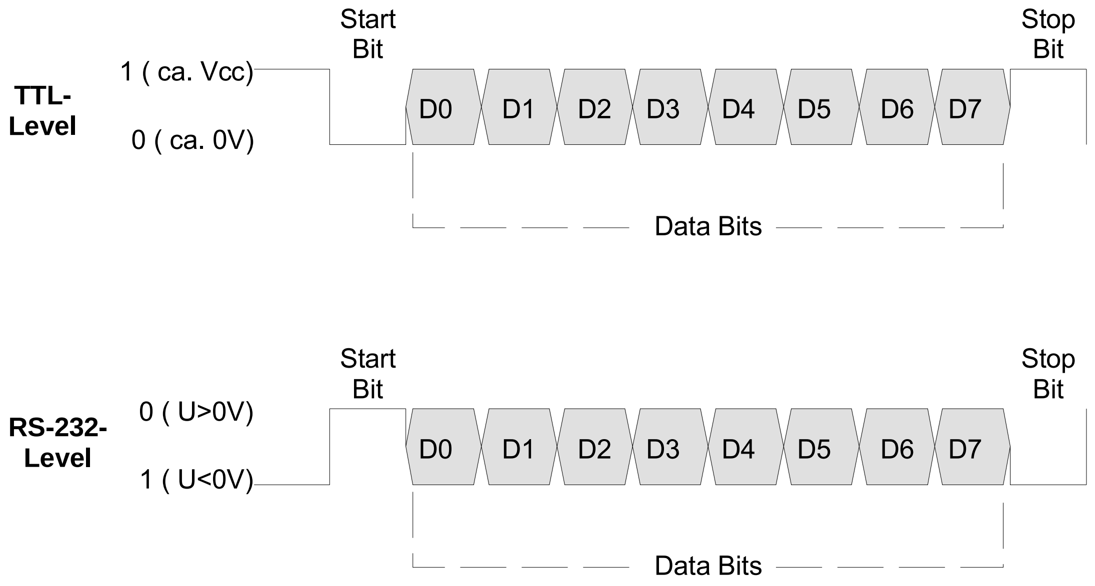


Figure 77: NMEA format (TTL and RS-232 level)

The different levels must be taken into consideration depending on whether the GNSS receiver used has a TTL or RS-232 interface (Figure 77):

- 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 GNSS module with a TTL level interface is connected to an appliance with an RS-232 interface, a level conversion must be effected (see 7.3.4).

Most GNSS receivers allow the baud rate to be increased (up to 115200 bits per second).

Each GNSS data set is formatted 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>

Table 17 explains the functions of individual characters and character groups.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS appliance
DTS	Data set identifier (e.g. RMC)
Inf_1 to 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 17: 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 GNSS receiver (Table 18):

$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 18: Recording of an NMEA protocol

7.2.1.2 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 19.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 19: Description of the individual GGA data set blocks

7.2.1.3 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 20.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 20: Description of the individual GGL data set blocks

7.2.1.4 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).

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 described in Table 21.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 21: Description of the individual GSA data set blocks

7.2.1.5 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 22.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 22: Description of the individual GSV data set blocks

7.2.1.6 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. All GNSS receivers relay this data set.

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 23.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 23: Description of the individual RMC data set blocks

7.2.1.7 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 24.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 24: Description of the individual VTG data set blocks

7.2.1.8 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 25.

Field	Description
$	Start of the data set
GP	Information originating from a GNSS 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 25: Description of the individual ZDA data set blocks

7.2.1.9 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 26)
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 26: Determining the checksum in the case of NMEA data sets

7.2.2 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 recognized around the world as the industry standard [xxviii]. 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.

7.2.2.1 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 [xxix] and which reference station has determined the correction data (Figure 78from [xxx]).

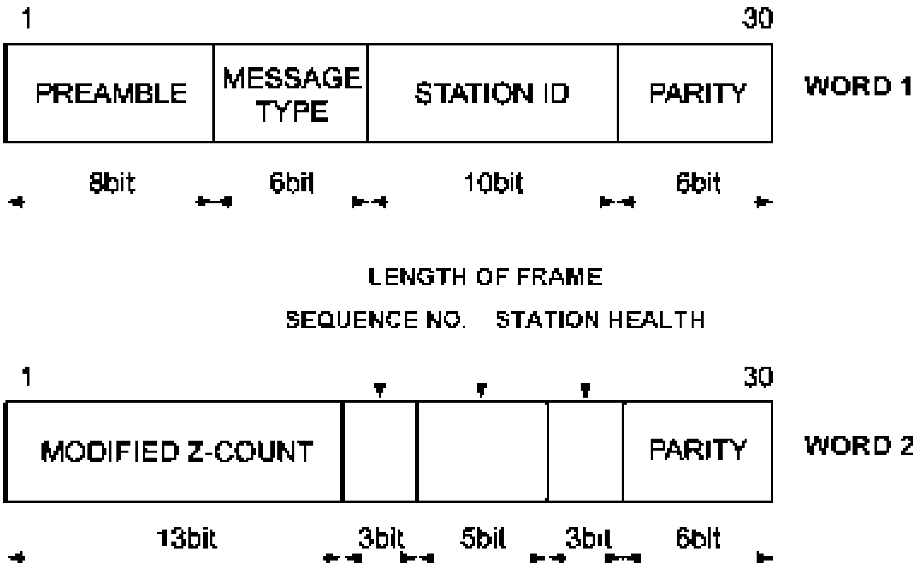


Figure 78: Construction of the RTCM message header

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 27: Contents of the RTCM message header

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

7.2.2.2 RTCM message type 1

Message type 1 transmits pseudorange correction data (PSR correction data, range correction) for all GNSS 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 79, extract from [xxxi], only WORD 3 to WORD 6 are shown).

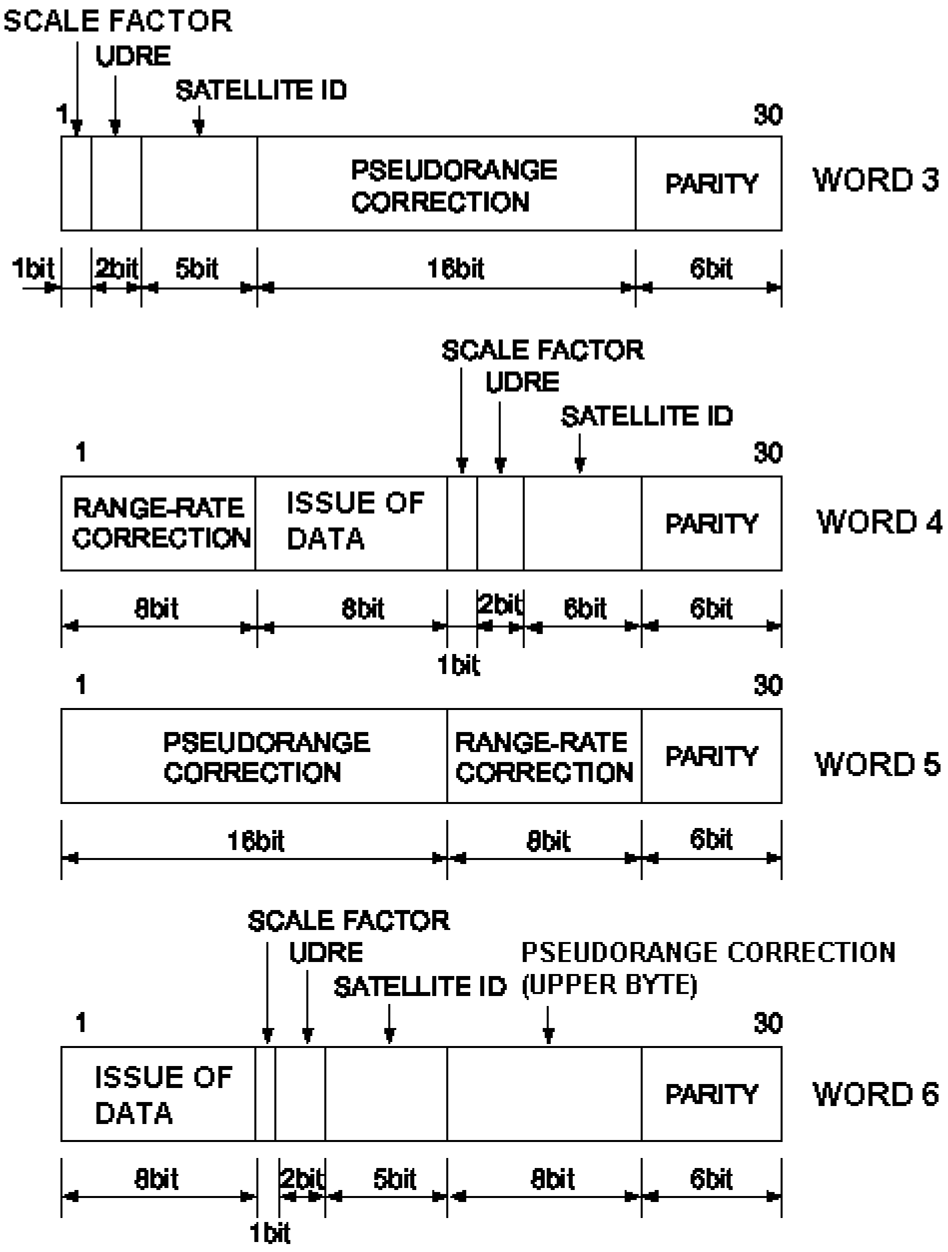


Figure 79: Construction of RTCM message type 1

Contents	Name	Description
SCALE FACTOR	Pseudorange 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	Pseudorange correction value	Effective range correction
RANGE-RATE CORRECTION	Pseudorange 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 28: Contents of RTCM message type 1

7.2.2.3 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 GNSS 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 [xxxii]). 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 [xxxiii].

7.2.3 Proprietary data interfaces

The majority of manufacturers offer proprietary data interfaces for their GNSS receivers. In comparison to the NMEA standard, proprietary data interfaces have the following advantages:

- Emission of an augmented data scope; e.g. information which is not supported by the NMEA Protocol.
- Higher data density: most proprietary protocols use binary data formats with which numerical and Boolean information can be transmitted in a more consolidated way. Data intensive notifications e.g. satellite ephemeris, can be contained in a notification. With higher data density, a higher emission interval with a constant data transmission speed can be carried out.
- Extensive configuration possibilities for the GNSS receiver.
- Optimal linking to manufacturer-specific evaluation and visualization tools enables precise analysis of the reception behavior.
- Possibility of downloads from the current versions of the manufacturer-specific GNSS firmware. This function is only supported in GNSS receivers with the suitable Flash memory.

- From the GNSS manufacturer's point of view, an improved distribution of GNSS information to different data sets with the objective of avoiding redundancy and the transmission of data which are not required for the application.
- Very good integrity security provided by checksums.
- Minimum work for the host computer in reading and accepting the received data. The conversion of numerical data into ASCII format in an internal binary format is not required.

Three different types of proprietary data interfaces are typically used:

- Additional NMEA data sets: the information is coded into usual NMEA data format (text based, separation of the data with commas etc.). However, immediately after the initial symbol (Dollar sign) a manufacturer-specific address data follows. Many GNSS manufacturers use the additional notifications to convey further frequently used information. The NMEA format is, however, not suitable for efficiently sending large amounts of information due to inadequate data density and the intensive conversion of binary data into text format.
- Binary format (e.g. u-blox UBX).
- Text based format.

7.2.3.1 Example: UBX protocol for *u-blox 5* GNSS receivers by u-blox AG

Apart from NMEA and RTCM, the ANTARIS® and u-blox 5 GNSS receivers by u-blox support the binary UBX protocol. As with the NMEA format, a framework format is given as follows:

Symbol	SYNC CHAR 1, 2	CLASS	ID	LENGTH	PAYLOAD	CHECKSUM
Explanation	Synchronization character	Message class	Message identification	Length of the data block	Structured data content	Checksum
Length (Bytes)	2	1	1	2	LENGTH	2
		Checksum coverage area				

Figure 80: Structure of the UBX data sets

Each data set begins with two constant synchronization characters (Hexadecimal values: always B5, 62). These characters are used for recognizing the start of a new data set. The following two fields, CLASS and ID, identify the data set type. This two-tier identification allows a clean structuring of the different data sets according to classes. The overview is obtained also after adding new data sets. Symbolic concepts, which are easy to understand such as "NAV-POSLLH" (CLASS 01, ID 02), are used for the documentation. Following this, the length information and the actual data content are given. u-blox stipulates specific data types for the data content. Finally, each data set ends with a 2-byte checksum. A dataset is only valid if the correct synchronization characters are available and the calculated and predetermined checksum coincide.

Message class	Description	Content (Extract)
NAV (01)	Navigation information	Position, speed, time, DGPS and SBAS information
RXM (02)	Receiver Management: Amplified GNSS reception data	GNSS raw data, e.g. pseudo-ranges, ephemeris, yearbook, satellite status
CFG (06)	Configuration notifications (Configure and request)	Serial interfaces, emission interval, reception and navigation parameters, energy saving methods
ACK (05)	Reception confirmation of the configuration notifications	Accepted or rejected
MON (0A)	Operational status of the GNSS receiver	CPU capacity utilization, condition of the operating system, use of system resources, antenna monitoring
AID (0B)	Feeding of auxiliary information to accelerate the start up.	Ephemeris, yearbook, cold start, last position, time, satellite status
INF (04)	Issuing of text based information notifications	
TIM (0D)	Configuration time pulse and time measurement of input signals	
UPD (09)	Download of new software	
USR (4*)	User specific notifications	

Table 29: Message classes (Hexadecimal values in brackets)

With the aid of customer specific software additional data sets can be integrated to existing protocols or additional user-specific protocols. Furthermore, ANTARIS® and u-blox-5 supports several protocols on the same interface, e.g. nested NMEA and UBX data sets in both directions so that the advantages of several protocols can be made use of.

7.3 Hardware Interfaces

7.3.1 Antennas

GNSS signals are right-hand circular polarized (RHCP). This requires a different type of antenna than the well-known whip antennas typically used for linear polarized signals.

GNSS modules operate with either a passive or active antenna. An active antenna contains a built-in LNA (Low Noise Amplifier) preamplifier. The GNSS receiver provides power to the active antenna over the RF signal line. For mobile navigation purposes a combined antenna (e.g. GSM/FM and GNSS) is supplied.

A smaller antenna will present a smaller aperture to collect the signal energy from the sky resulting in a lower overall gain. There is no way to get around this problem. Amplifying the signal after the antenna will not improve the signal to noise ratio.

The two most common types of GNSS antenna available on the market are the Patch and the Helix antenna. This section will describe a variety of different kinds of antennas used in GNSS technology.

7.3.1.1 Patch Antenna

The most common antenna type for GNSS applications is the patch antenna.

Patch antennas are flat, generally have a ceramic and metal body and are mounted on a metal base plate. They are often cast in a housing.

Patch antennas are ideal for applications where the antenna is mounted on a flat surface, e.g. the roof or the dashboard of a car. Patch antennas can demonstrate a very high gain, especially if they are mounted on top of a large ground plane (70 x 70 mm). Ceramic patch antennas are very popular because of low costs and the huge variety of available sizes.

Figure 81: Patch Antennas

7.3.1.2 Helix Antenna

Another type of antenna used in GNSS applications is the helix antenna.

Helix antennas are cylindrical in shape and are typically used where multiple antenna orientations are possible. They are robust and show good navigation performance.

The actual geometric size depends on the dielectric that is used to fill the space between the active parts of the antenna. If the antenna is only filled with air it needs to be comparatively large (60mm length x 45mm diameter). Using materials with a high dielectric constant results in a much smaller form factor. Sizes in the order of 18mm length x 10mm diameter are available on the market. The smaller the dimensions of the antenna, the greater the influence tight manufacturing tolerances have on performance.

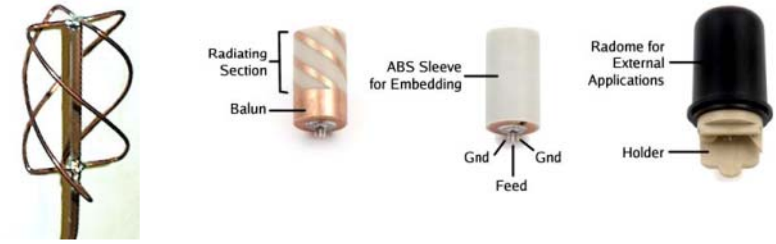


Figure 82: Helix Antennas

7.3.1.3 Chip Antenna

Chip antennas are smaller than patch or helical antennas. They offer a wide range of sizes down to (11.0 x 1.6 x 1.6 mm). Since current trends are for increasing miniaturization, they are becoming more popular. The available ground plane has a significant impact on their performance. Chip antennas are not recommended for applications where navigation precision is a core feature.

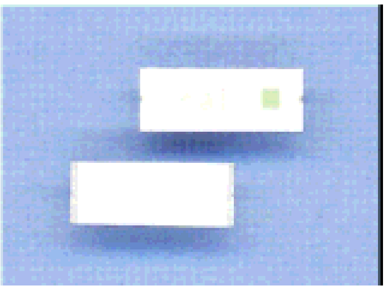


Figure 83: Chip Antenna

7.3.1.4 Fractal Element Antennas (FEA)

A fractal antenna is an antenna that uses a self-similar design to maximize the length, or increase the perimeter (on inside sections or the outer structure), of material that can receive or transmit electromagnetic signals within a given total surface area. For this reason, fractal antennas are very compact.

Fractal antennas have a 3dB loss compared to helical or patch antennas due to the linear polarization. And they show a strong dependency on the size of the ground plane.

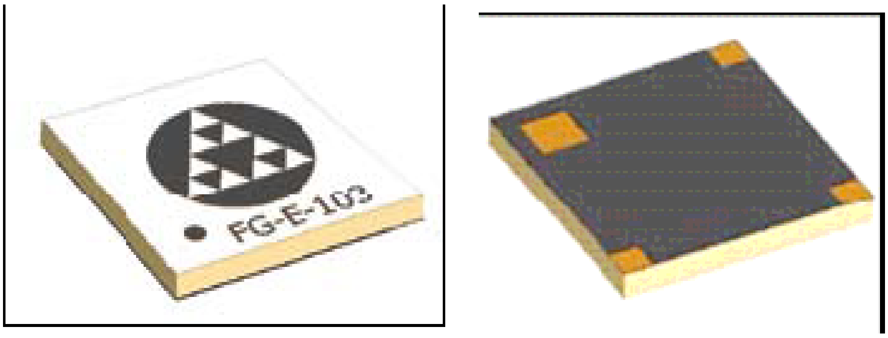


Figure 84: Fractal Chip Antenna top and bottom view

7.3.1.5 Dipole Antenna

Dipole antennas can be a very cost effective solution, especially when printed on PCB. They show an acceptable performance in indoor environments. The field does not depend on the ground plane.

Dipole antennas are linear, not circular polarized. This results in a 3dB loss in open space for GPS but has some advantage for the backlobe, which is helpful for indoor reception.

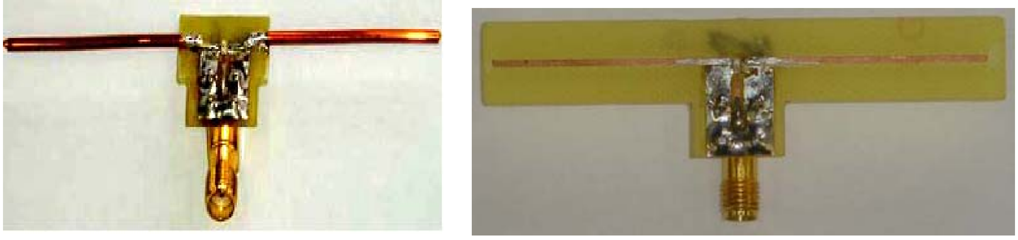


Figure 85: Dipole and Printed PCB Dipole Antenna

7.3.1.6 Loop Antenna

Loop antennas are typically printed on a sticker, which can for example be attached to a windshield. When mounted this way loop antennas demonstrate good navigation performance. Since the field is not dependant on a ground plane, the impedance and center frequency are not very sensitive to objects near the field.

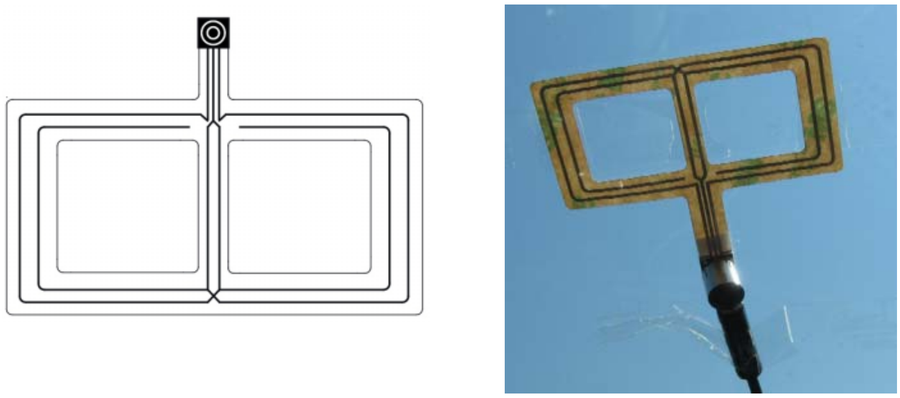


Figure 86: Loop Antenna, Laser Antenna 775

7.3.1.7 Planar Inverted F Antenna (PIFA)

The PIFA antenna literally looks like the letter 'F' lying on its side with the two shorter sections providing feed and ground points and the 'tail' (or top patch) providing the radiating surface. PIFAs make good embedded antennas in that they exhibit a somewhat omni directional pattern and can be made to radiate in more than one frequency band. They are linear polarized with only moderate efficiency. PIFA are used in cellular phones (E-911) but it is not recommended to use them in applications where navigation precision is a core feature.

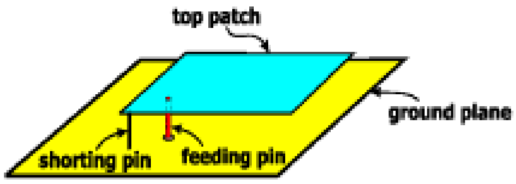


Figure 87: Planar inverted-f-antenna (PIFA)

Figure 88: Ceramic Planar inverted-f-antenna (PIFA) and PIFA for a cellular phone

7.3.1.8 High Precision GNSS Antennas

For applications requiring high accuracy such as surveying or timing, some very precise antenna systems exist. Common to these designs are large size, high power consumption and high price. High precision antennas are not generally used for mass-market GNSS applications.

These antnenna designs are highly optimized to suppress multi-path signals reflected from the ground (choke ring antennas, multi-path limiting antennas, MLA). Another area of optimization is accurate determination of the phase center of the antenna. For precision GNSS applications with position resolution in the millimeter range it is important that signals from satellites at all elevations virtually meet at exactly the same point inside the antenna. For this type of application receivers with multiple antenna inputs are often required.

7.3.1.8.1 Choke Ring and Pinwheel™ technology (Novatel) antennas

Choke Ring antennas are high performance GPS antennas. The co-central rings around are suppressing the reflected signals from the ground and therefore it's multi-path sensitivity.

Pinwheel Technology offers excellent multipath suppression, with the suppression rings being printed on PCB.

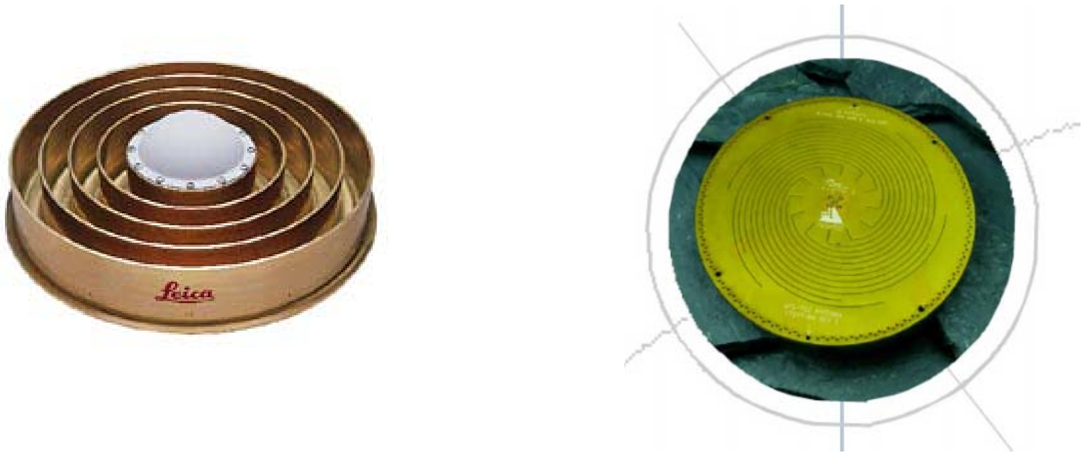


Figure 89: Leica Choke Antenna AT504 and Pinwheel™ Antenna (Novatel)

7.3.2 Supply

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

7.3.3 Time pulse: 1PPS and time systems

Most GNSS receivers generate a time pulse every second, referred to as 1 PPS (1 pulse per second), which is synchronized to UTC. This signal usually has a TTL level (Figure 90).

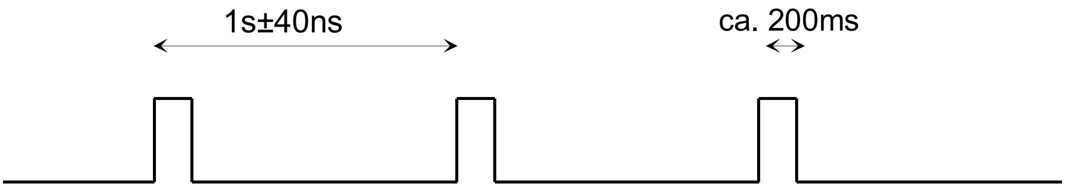


Figure 90: 1PPS signal

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

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

7.3.3.1 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 GNSS 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.

7.3.3.2 Universal Time Coordinated (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 coordinated 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).

7.3.3.3 GPS time

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 (these are the leap seconds or UTC offset).

7.3.3.4 Satellite time

Because of constant, irregular frequency errors in the atomic clocks onboard the GNSS satellites, individual satellite time is at variance with GPS system time. Control stations monitor satellite clocks and any apparent time disparity is relayed to Earth. Any time differences must be taken into account when conducting local GNSS measurements.

7.3.3.5 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 30) on June 21st, 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 30: Time systems

The interrelationship of time systems (valid for 2006):

TAI – UTC = +33sec

GPS – UTC = +14sec

TAI – GPS = +19sec

7.3.4 Converting the TTL level to RS-232

7.3.4.1 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, GNSS 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 4800, 9600, 19200, 38400, 57600 and 115200 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.

A start bit identifies the beginning of a data word, 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.

7.3.4.2 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 91) illustrates the difference between TTL and RS-232 levels. Level inversion can clearly be seen.

Figure 91: Difference between TTL and RS-232 levels

7.3.4.3 Converting the TTL level to RS-232

Many GNSS receivers and GNSS 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" [xxxiv] is illustrated on the following circuit diagram (Figure 92). 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.

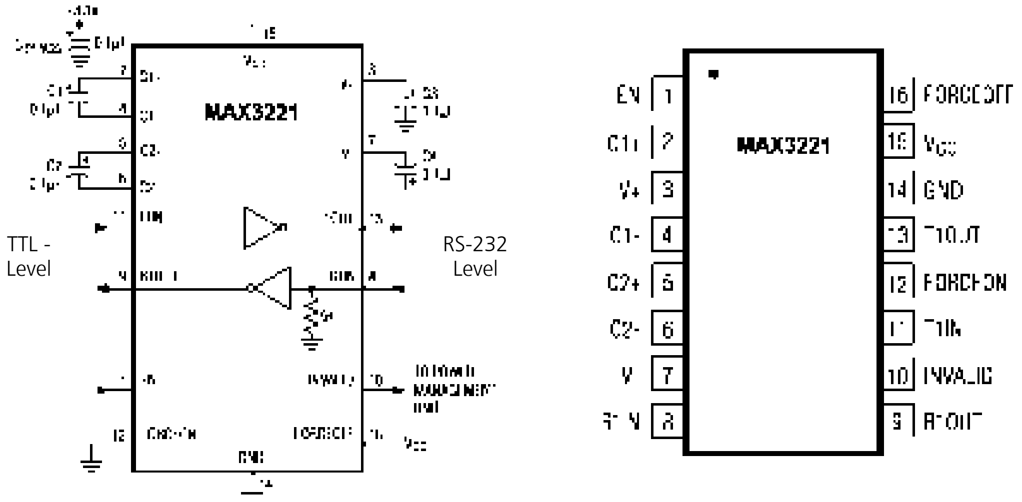


Figure 92: Block diagram pin assignment of the MAX32121 level converter

The following test circuit (Figure 93) 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.

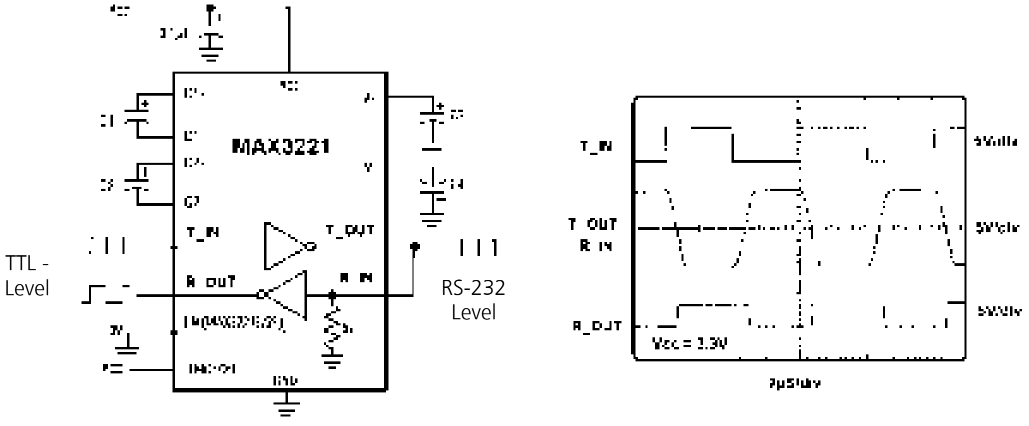


Figure 93: Functional test on the MAX3221 level converter

8 GNSS RECEIVERS

If you would like to . . .

- know how a GNSS receiver is constructed
- understand why several stages are necessary to reconstruct GNSS signals
- know how an RF 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!

8.1 Basics of GNSS handheld receivers

A GNSS receiver can be divided into the following main stages (Figure 61).

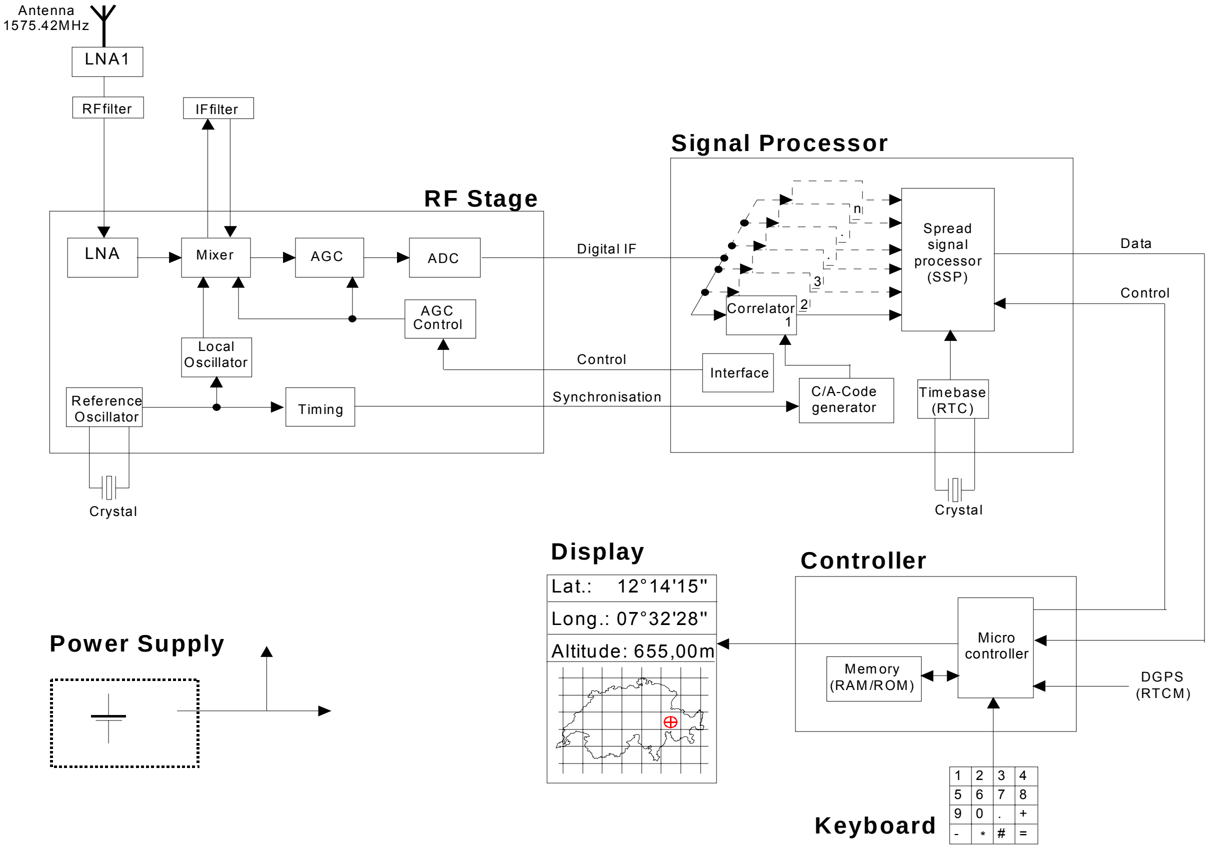


Figure 94: Simplified block diagram of a GNSS receiver

- **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.
- **RF filter:** The GNSS signal bandwidth is approx. 2MHZ. The RF filter reduces the affects of signal interference. The RF stage and signal processor actually represent the special circuits in a GNSS receiver and are adjusted to each other.
- **RF stage:** The amplified GNSS 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 digitalized via Amplitude Gain Control (AGC)
- **IF filter:** The intermediate frequency is filtered out using a bandwidth of several MHz. 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 RF stage and signal processor are simultaneously switched to synchronize 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 programmed 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.
- **Power supply:** The power supply delivers the necessary operational voltage to all electronic components.

8.2 GNSS Receiver Modules

8.2.1 Basic design of a GNSS module

GNSS 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 synchronized 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 GNSS module issues information on the constellation, satellite health, and the number of visible satellites etc.

Figure 95 shows a typical block diagram of a GNSS 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 an ADC.

Signal travel time from the satellites to the GNSS receiver is determined by correlating PRN pulse sequences. The satellite PRN sequence must be used to establish 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 [XXXV]. Up to 16 satellite signals are processed simultaneously. A signal processor carries out the control and generation of PRN sequences and the recovery of data. Calculating and saving the position, including the variables derived from this, is carried out by a processor with a memory facility.

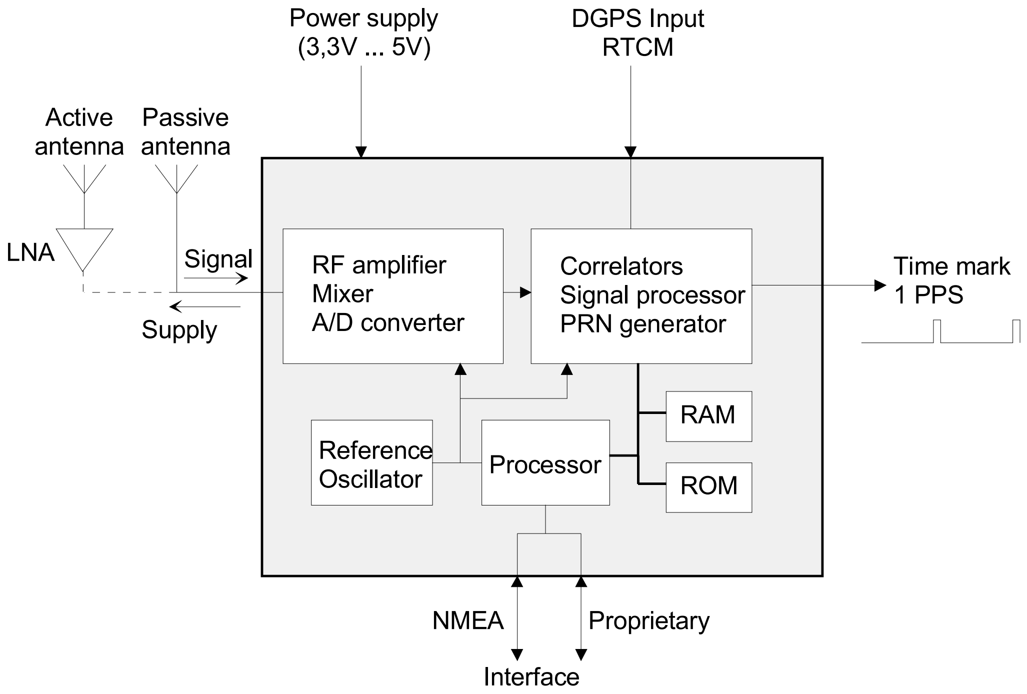


Figure 95: Typical block diagram of a GNSS module

8.2.2 Example: *u-blox 5*

u-blox 5 chips have been specifically designed for applications with tight cost, size and power constraints that require ultra-fast acquisition and high-precision tracking. The highly integrated architecture brings full positioning functionality, from antenna input to position data output, in a self-contained solution that requires few external components. Moreover, innovative power hardware and software features enable the engine to operate on as little as 50 mW. This ensures long battery life times, a critical feature for portable applications.

u-blox 5 chips compute positions instantly and accurately. A dedicated acquisition engine with over 1 million effective correlators is capable of massive parallel searches across the time/frequency space. This makes satellite acquisition possible in less than 1 second while long integration times enable a –160 dBm acquisition sensitivity. Acquired satellites are then passed on to a tracking engine. This setup allows for the GNSS engine to simultaneously track up to 16 satellites and search for new ones.

The on-chip Power Management Unit (PMU) enables a single supply voltage source and features a switch-mode DC/DC converter that optimizes power efficiency and extends the supply voltage range. All required core and I/O voltages are generated internally by means of LDOs (Low-Drop-Out).

When GALILEO-L1 signals become available, *u-blox 5* receivers will be capable of receiving and processing them via a simple upgrade. The ability to receive and track GALILEO satellite signals will result in higher coverage, improved reliability and better accuracy. The chip’s advanced jamming suppression mechanism automatically filters signals from interfering sources, thus maintaining high GNSS performance.

The u-blox 5 single chip consists of two ICs assembled into a single package, often referred to as 'SiP' or ’System in Package’. This enables the independent selection of the optimal technology for the RF-IC and for the baseband-IC. The RF-IC is diffused on 0.18 µm RF-CMOS technology while the baseband-IC is on 0.13 µm CMOS. Alternatively, the two ICs can be assembled into two separate packages. This chipset solution provides an external bus interface to connect an external memory. For a simplified block diagram see Figure 96.

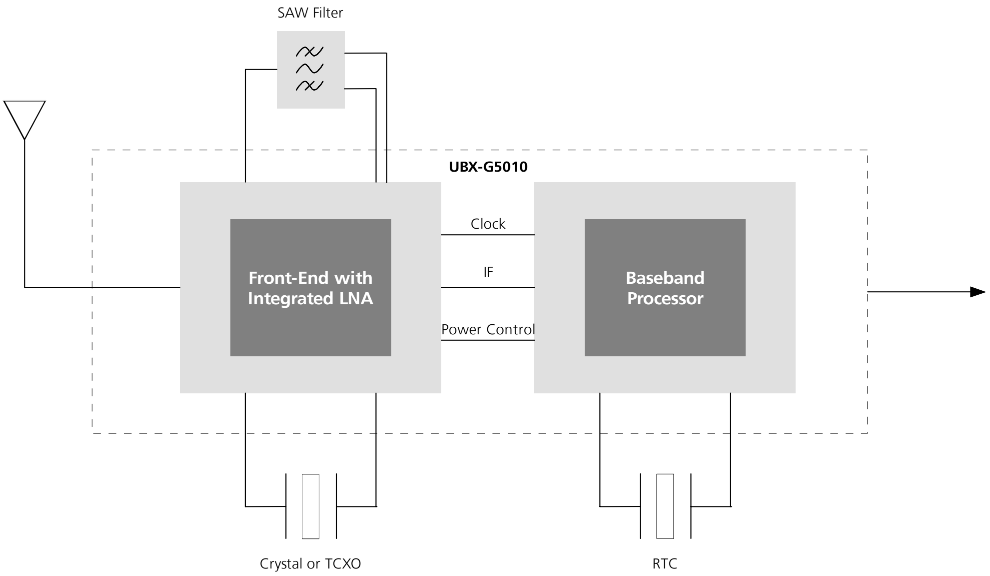


Figure 96: Block diagram of u-blox 5 chipset

9 GNSS Applications

If you would like to . . .

- know what variables can be determined using GNSS
- know what applications are possible with GNSS
- know how time is precisely determined

then this chapter is for you!

9.1 Introduction

Using GNSS the following two values can be determined anywhere on Earth:

- Exact position (longitude, latitude and height co-ordinates) accurate to within a range of 20 m to approx. 1mm
- Precise time (Universal Time Coordinated, UTC) accurate to within a range of 60ns to approx. 1ns.

In Addition, other values can also be determined, such as:

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

The established fields for GNSS usage are surveying, shipping and aviation. However, satellite navigation is currently enjoying a surge in demand for Location Based Services (LBS) and systems for the automobile industry. Applications, such as Automatic Vehicle Location (AVL) and the management of vehicle fleets also appear to be on the rise. In addition, GNSS is increasingly being utilized in communications technology. For example, the precise GNSS time signal is used to synchronize telecommunications networks around the world. Since 2001, the US Federal Communications Commission (FCC) has required that, when Americans call 911 in an emergency, their position be automatically determined to within approx. 125m. This law, known as E-911 (Enhanced 911), necessitates that mobile telephones be upgraded with this new technology.

In the leisure industry, GNSS is becoming increasingly widespread and important. Whether hiking, hunting, mountain biking, or windsurfing across Lake Constance in Southern Germany, a GNSS receiver provides invaluable information for a great variety of situations.

GNSS can essentially be used anywhere on Earth where satellite signal reception is possible and knowledge of position is of benefit.

9.2 Description of the various applications

GNSS aided navigation and positioning is used in many sectors of the economy, as well as in science, technology, tourism, research and surveying. GNSS can be utilized wherever precise three-dimensional positional data has a significant role to play. A few important sectors are detailed below.

9.2.1 Location Based Services (LBS)

Location Based Services (LBS) are services based on the current position of a user (e.g. Mobile Communications Network users equipped with a cell-phone). Normally the mobile station (e.g. cell-phone) must be logged on and its position given in order to request or obtain specific information/services from the provider. An example of this is the distribution of local information, such as the location of the nearest restaurant or automatically providing the caller position to emergency number services (E-911 or E-112).

The prerequisite for LBS is the determination of accurate position information. Location is determined either through signals from the cell-phone network or through using satellite signals.

The location of the user is either given with absolute geographic coordinates (longitude and latitude) or relative to the position of a given reference point (e.g. "the user is located within a radius of 500m to the monument…"). There are basically two kinds of services provided, known as "push services" or "pull services". A push service sends the user information on the basis of his or her position without their having to request it (e.g. "In the vicinity is …"). A pull service requires that the user first request the information from the service (e.g. calling an emergency number E-911 or E-112).

Knowing location is of critical importance for surviving emergencies. However, public security and rescue services have shown in a study that 60% of those making emergency calls with mobile telephones were unable to communicate their exact position (in comparison to 2% of callers from fixed-net telephones). Every year within the European Union there are 80 million emergency calls made, of these 50% are made with mobile telephones.

The determination of the user's position can either be obtained within the mobile station or by the mobile network. For determining the position the mobile station refers to information from the mobile communication network or satellite signals.

Countless technologies for positioning have already been introduced and have been standardized. Few of these are currently being used and it remains to be seen if all the ideas will ever be realized. In Europe, the most common applications currently being used are:

- Position determination through the identification of active cells in the cell-phone network (Cell-ID). This procedure is also known as Cell of Origin (COO) or Cell Global Identity (CGI).
- Position determination by the time delay of GSM-Signals TA (Timing Advance). TA is a parameter in GSM-Networks through which the distance to the base station can be determined.
- Satellite Positioning through Satellite Navigation: e.g. GNSS

9.2.2 Commerce and Industry

For the time being, road transportation continues to be the biggest market for GNSS. Of a total market value estimated at 60 billion US-$ in 2005, 21.6 billion alone was accounted for by road transportation and 10.6 billion by telecommunications technology [xxxvi]. Vehicles will be equipped with a computer and a screen, so that a suitable map showing position can be displayed at all times. This will enable selecting the best route to the destination. During traffic jams alternative routes can be easily determined and the computer will calculate the journey time and the amount of fuel needed to get there.

Vehicle navigation systems will direct the driver to his or her destination with visual and audible directions and recommendations. Using the necessary maps stored on CD-ROM and position estimates based on GNSS, the system will determine the most favorable routes.

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

GNSS can be used for locating vehicles or as an anti-theft device. Armored cars, limousines and trucks carrying valuable or hazardous cargo will be fitted with GNSS. An alarm will automatically be set off if the vehicle deviates from its prescribed route. With the press of a button the driver can also operate the alarm. Anti-theft devices will be equipped with GNSS receivers, allowing the vehicle to be electronically immobilized as soon as monitoring centers receive a signal.

GNSS can assist in emergency calls. This concept has already been developed to the marketing level. An automobile is equipped with an onboard GNSS receiver connected to a crash detector. In the event of an accident this signals an emergency call center providing precise information about which direction the vehicle was traveling and its current location. As a result, the consequences of an accident can be made less severe and other drivers can be given advanced warning.

Railways are other highly critical transportation applications, where human life is dependent on technology functioning correctly. Precautions need to be taken here against system failure. This is typically achieved through backup systems, where the same task is performed in parallel by redundant equipment. During ideal operating situations, independent sources provide identical information. Well-devised systems indicate (in addition to a standard warning message) if the available data is insufficiently reliable. If this is the case, the system can switch to another sensor as its primary data source, providing self-monitoring and correction. GNSS can provide a vital role here in improving system reliability and safety.

Other possible uses for GNSS include:

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

9.2.3 Communications Technology

Synchronizing computer clocks is vital in situations with separated processors. The foundation of this is a highly accurate reference clock used to receive GNSS satellite signals along with Network Time Protocol (NTP), specified in RFC 1305.

Other possible uses for GNSS include:

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

9.2.4 Agriculture and Forestry

GNSS contributes to precision farming in the form of area and use management, and the mapping of sites in terms of yield potential. In a precision farming system, combined harvest yields are recorded by GNSS and processed initially into specific plots on digital maps. Soil samples are located with the help of GNSS and the data added to the system. Analysis of these entries then serves to establish the amount of fertilizer that needs to be applied to each point. The application maps are converted into a form that onboard computers can process and are transferred to these computer using memory cards. In this way, optimal practices can be devised over a long term that can provide high time /resource savings and environmental conservation.

Other possible uses for GNSS include:

- Use and planning of areas
- Monitoring of fallow land
- Planning and managing of crop rotation
- Use of harvesting equipment
- Seeding and spreading fertilizer
- Optimizing logging operations
- Pest management
- Mapping diseased and infested areas

For the forest industry as well, there are many conceivable GNSS 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:

- Optimizing log transportation: By equipping commercial vehicle fleets with onboard computers and GNSS, and using remote data transfer facilities, transport vehicles can be efficiently directed from central operations units.
- Inventory Management: Manual identification prior to timber harvesting is made redundant by satellite navigation. For the workers on site, GNSS can be used as a tool for carrying out specific instructions.
- Soil Conservation: By using GNSS, remote roads and tracks used in harvesting wood can be identified and their frequency of use established.
- Management of private woodlots: In wooded areas divided up into small parcels, cost-effective and highly mechanized harvesting processes can be employed using GNSS, allowing the transport of increased quantities of timber.

9.2.5 Science and Research

With the advent of the use of aerial and satellite imaging in archaeology, GNSS has also become firmly established in this field. By combining GIS (Geographic Information Systems) with satellite and aerial photography, as well as GNSS and 3D modeling, it has been possible to answer some of the following questions:

- What conclusions regarding the distribution of cultures can be made based on the location of the finds?
- Is there a correlation between areas favoring the growth of certain arable plants and the spread of certain cultures?
- What did the landscape look like in this vicinity 2000 years ago?

Surveyors use (D)GPS, in order to carry out surveys (satellite geodesy) quickly and efficiently to within an accuracy of a millimeter. For surveyors, the introduction of satellite-based surveying represents a progress comparable to that between the abacus and the computer. The applications are endless. These range from land registry and property surveys to surveying roads, railway lines, rivers and the ocean depths. Geological variations and deformations can be measured and landslides and other potential catastrophes can be monitored, etc.

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

GNSS already has an established place in photogrammetry. Apart from determining co-ordinates for ground reference points, GNSS is regularly used to determine aerial survey navigation and camera co-ordinates for aero-triangulation. Using this method, over 90% of ground reference points can be dispensed with. Future reconnaissance satellites will be equipped with GNSS receivers to aid the evaluation of data for producing and updating maps in underdeveloped countries.

In hydrography, GNSS can be used to determine the exact height of a survey boat. This can simplify the establishment of clearly defined reference points. The expectation is that usable GNSS procedures in this field will be operational in the near future.

Other possible areas of application for GNSS are:

- Archaeology
- Seismology (geophysics)
- Glaciology (geophysics)
- Geology (mapping)
- Surveying deposits (mineralogy, geology)
- Physics (flow measurements, time standardization 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

9.2.6 Tourism / Sport

In sailplane and hang glider competitions GNSS receivers are often used to maintain protocols with no risk of bribery.

GNSS can be used to locate persons who have found themselves in a maritime or alpine emergency. (SAR: Search and Rescue)

Other possible uses for GNSS include:

- Route planning and selecting points of particular significance (natural and culturally/historically significant monuments)
- Orienteering (training routes)
- Outdoor activities and trekking
- Sporting activities

9.2.7 Military

GNSS is used anywhere where combatants, vehicles, aircraft and guided missiles are deployed in unfamiliar terrain. GNSS 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 GNSS signal (PPS) is used for military applications, and can only be used by authorized agencies.

9.2.8 Time Measurement

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

Currently, the most common method for making precision time comparisons between clocks in different places is a "common-view" comparison with the help of GNSS satellites. Institutes that wish to compare clocks measure the same GNSS satellite signals at the same time and calculate the time difference between the local clocks and GNSS system time. As a result of the differences in measurement, the difference between the clocks at the two institutes can be determined. Because this involves a differential process, GNSS 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 GNSS, is also relayed to the International Bureau for Weights and Measures (BIPM) in Paris for calculating the international atomic time scales TAI and UTC.

A Resources in the World Wide Web

If you would like to...

- know, where you can get more information about GNSS
- know, where the GPS system is documented
- become a GNSS expert

then this chapter is for you!

A.1 Summary reports and 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, http://www.edu-observatory.org/gps/gps.html
NMEA-0183 and GPS Information by Peter Bennett, http://vancouver-webpages.com/peter/
Joe Mehaffey, Yeazel and Dale DePriest's GPS Information http://gpsinformation.net
The Global Positioning Systems (GPS) Resource Library http://www.gpsy.com/gpsinfo/
GPS SPS Signal Specification, 2nd Edition (June 2, 1995), USCG Navigation Center http://www.navcen.uscg.gov/pubs/gps/sigspec/default.htm

A.2 Differential GPS

Differential GPS (DGPS) by Sam Wormley, http://www.edu-observatory.org/gps/dgps.html
DGPS corrections over the Internet http://www.wsrcc.com/wolfgang/gps/dgps-ip.html
EGNOS Operations Manager http://www.essp.be/
Wide Area Differential GPS (WADGPS), Stanford University http://waas.stanford.edu/

A.3 GPS institutes

Institute for applied Geodesy: GPS information and observing system 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 http://www.rin.org.uk/
The Institute of Navigation http://www.ion.org/
University NAVSTAR Consortium (UNAVCO) http://www.unavco.org

A.4 GNSS antennas

REEL Reinheimer Electronic Ltd. http://www.reinheimer-elektronik.de/
WISI, WILHELM SIHN JR. KG http://www.wisi.de/
Matsushita Electric Works (Europe) AG http://www.mew-europe.com/gps/en/news.html
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/

A.5 GNSS newsgroup and GNSS technical journal

Newsgroup: sci.geo.satellite-nav http://groups.google.com/groups?oi=djq&as_ugroup=sci.geo.satellite-nav
Technical journal : GPS World (appears monthly) http://www.gpsworld.com

B Index

B.1 List of Figures

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B.3 Sources

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[xx] Bundesamt für Landestopographie: http://www.swisstopo.ch

[xxi] Elliott D. Kaplan: Understanding GPS, Artech House, Boston 1996,
ISBN 0-89006-793-7

[xxii] http://www.tandt.be/wis

[xxiii] http://www.egnos-pro.esa.int/IMAGEtech/imagetech_realtime.html

[xxiv] http://igscb.jpl.nasa.gov/

[xxv] GPS-World, November 2003: Vittorini und Robinson: Optimizing Indoor GPS Performance, page 40

[xxvi] www.maxim-ic.com/quick_view2.cfm Datenblatt MAX2640, MAX2641

[xxvii] NMEA 0183, Standard For Interfacing Marine Electronics Devices, Version 2.30

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[xxix] Global Positioning System: Theory and Applications, Volume II, Bradford W. Parkinson, page 31

[xxx] User Manual: Sony GXB1000 16-channel GPS receiver module

[xxxi] User Manual: Sony GXB1000 16-channel GPS receiver module

[xxxii] swipos, Positionierungsdienste auf der Basis von DGPS, page 6, Bundesamt für Landestopographie

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