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EGNOS AUGMENTED SATELLITE POSITIONING

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Abstract: This thesis studies how GPS positioning accuracy can be improved with EGNOS corrections. EGNOS corrects GPS satellites' track and clock errors. Additionally, EGNOS provides means to improve the estimation of GPS signal delay in atmosphere. The thesis also describes a practical EGNOS application implemented in a TETRA radio.

Tiivistelmä: Tämä pro gradu -työ tutkii GPS-paikannuksen tarkkuuden parantamista EGNOS-avusteiden avulla. EGNOS korjaa GPS-satelliittien rata- ja kellovirheitä. Lisäksi EGNOS-järjestelmän avulla voidaan parantaa GPS-signaalin ilmakehäviiheen arviointia. Työ myös kuvaa käytännön EGNOS-sovelluksen TETRA-radiossa.

Foreword

First of all I would like to thank my girlfriend Saija for continuous support and numerous proof readings. This would have been a much longer journey without your help. I must also thank my instructor Vesa Klememettinen at EADS Secure Networks Oy, who has guided the thesis to right direction and helped with many technical problems I faced before completion. I would also like to thank my professor Tapani Ristaniemi for comments and guidance. Moreover I want to thank Petri Kujala and Mika Laitinen for the opportunity to make this thesis.

Writing this thesis has been more demanding task than I expected, but it seems that I will just meet the final deadline I had set. I have finalized my thesis with mixed feelings: It is great to finally get the work done, to graduate and to leave studies behind. On the other hand I am bit disappointed, as the results I obtained in the thesis did not meet the expectations I had set. However I guess sometimes one must also accept less than perfect results.

Terms and Abbreviations

Almanac	Coarse ephemeris data sent by GPS satellites
ASCII	American Standard Code for Information Interchange
ASSI	Alias SSI
ATSI	Alias TSI
Azimuth	Satellite's direction in the sky
C/A-code	Coarse/ Acquisition-Code
CCF	Central Control Facility
CDMA	Code Division Multiple Access
CPF	Central Processing Facility
CRC	Cyclic Redundancy Check
DGPS	Differential GPS
DMO	Direct Mode
DoD	Department of Defense
DOP	Dilution Of Precision
CR	Carriage Return
DS2DC	Data Server to Data Client
EDAS	EGNOS Data Access System
EGNOS	European Geostationary Navigation Overlay System

Ephemeris	Satellite's track data, which can be used to calculate satellite's position at a certain instant of time.
Epoch	Certain instant of time
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EWAN	EGNOS Wide Area Network
GEO	SBAS satellites on geostationary orbit
GIVEI	Grid Ionospheric Vertical Error Indicator
GLONASS	Russian satellite position system
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile communications
GSSI	Group SSI
GTSI	Group TSI
HOW	Handover Word
IGP	Ionospheric Grid Point
IOD	Issue Of Data
IODI	Issue Of Data Ionosphere
IODP	Issue Of Data PRN
ISDN	Integrated Services Digital Network

ISSI	Individual SSI
ITSI	Individual TSI
LF	Line Feed
Obliquity Factor	The effect of angle to ionospheric delay
MCC	Mobile Country Code
MNC	Mobile Network Code
MNI	Mobile Network Identity
NMEA	National Marine Electronics Association
NSAP	Network-layer Service Access Point address
OSI	Open Systems Interconnection
P-Code	Precise-Code
PDN	Packet Data Network
PDOP	Position DOP
PRN	Pseudo Random Noise
Pseudorange	Receiver distance to a satellite. Pseudo denotes that the range contains an error of unknown size.
PSTN	Public Switched Telephone Network
PTN	Private Telephone Network
RIMS	Ranging and Integrity Monitoring Stations
RRC	Range Rate Correction

RTCA	Radio Technical Commission for Aeronautics
SBAS	Satellite Based Augmentation System
SDS	Short Data Service
Sidereal day	Time it takes earth to turn 360 degrees in its rotation
SINCA	SISNeT Compression Algorithm
SISNeT	ESA internet service for EGNOS augmenting
SMI	Short Management Identity
SSI	Short Subscriber Identity
TCP/IP	Transmission Control Protocol/Internet Protocol
TEI	TETRA Equipment Identity
TETRA	Terrestrial Trunked Radio
TLM	Telemetry Word
TMI	TETRA Management Identity
TMO	Trunked Mode
TSI	TETRA Subscriber Identity
UDRE	User Differential Range Error
UDREI	User Differential Range Error Indicator
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System

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1 Introduction

Navigation and positioning is an important part of modern technology. In the recent years, Global Positioning System (GPS) has become part of everyday life. This thesis studies a one way of improving the accuracy of GPS.

GPS is based on triangulation from known satellite positions to an unknown receiver position. If GPS satellite's position is not accurate or the distance to the satellite is not accurately measured, the receiver position will neither be accurate. Chapter 2 explains the fundamentals of GPS; how it works, its main building blocks and history. Chapter 2 also covers the main causes of position error: satellite track inaccuracies, clock errors and the signal delay in atmosphere.

Chapter 3 describes how Differential GPS (DGPS) can be used to minimize the errors explained in chapter 2. One form of DGPS are Satellite Based Augmentation Systems (SBAS), such as European Geostationary Overlay System (EGNOS). EGNOS is an SBAS, which works in most of Europe, through three satellites orbiting earth over equator. Chapter 3 describes the principles of DGPS and SBAS, which is followed by a detailed technical description of different GPS correction messages sent by EGNOS. Later parts of the chapter describe how these corrections are applied to the measurements performed by a GPS receiver. Finally an alternative method to obtain EGNOS corrections in real-time through internet is introduced.

One field of GPS applications is mobile phones and radios. This research has been done on a professional mobile TERrestrial Trunked Radio (TETRA) terminal. TETRA is a European standard for terminals that are used by public safety organizations such as firemen and police. Even though TETRA is a European standard, there are TETRA networks and terminals all over world. Chapter 4 outlines the TETRA-standard focusing on the parts which are important for this research.

Chapter 5 describes an EGNOS augmentation application developed during this research. The application fetches EGNOS augmentation data through the internet and combines the data to GPS measurements. The GPS measurements and the augmentation application have

been done in a TETRA terminal. The chapter also introduces methods to collect measurement data.

The measurements for this research have been performed simultaneously with a non-augmented GPS and with the application described in chapter 5. Both systems use similar TETRA terminal and the only difference is that the other system is augmented with EGNOS messages. The aim of the measurements is to compare GPS accuracy to EGNOS augmented GPS. These measurements are described in chapter 6. Chapter 6 also analyses the measurement results and describes possible reasons for inaccurate results.

1.1 Objectives

The objectives of this thesis are to study the position accuracy that can be achieved with EGNOS augmentation and to study the effect of EGNOS augmentation to the GPS position accuracy. This is achieved by comparing the EGNOS position accuracy to the accuracy of stand-alone GPS. Furthermore, this thesis studies how a practical EGNOS application can be implemented in a TETRA terminal.

2 Global Positioning System (GPS)

GPS is a satellite based positioning system, which can be used anytime and anywhere on earth to determine position, speed and precise time. GPS consists of three segments: space segment, control segment and user segment. It has been designed and is maintained by the United States Department of Defense (DoD). Regardless of its military origins it is also widely used for civilian applications [1].

2.1 GPS Evolvement

GPS originates from sixties when US navy TIMATION and air force 621B projects were started. Both projects aimed to develop a satellite based navigation system. These projects were combined in 1973 and the first GPS-satellite was launched in 1978 [1]. After several delays GPS attained initial operational capability in 1993 and full operational capability in early 1995 [2]. There are six different satellite generations Block I, Block IA, Block II, Block IIA, Block IIR and Block IIR-M. Block I satellites were test satellites that were used to test the principles of satellite positioning. Later satellite generations have among other things improved satellite's clock precision and reprogramming capabilities. Current constellation consists of Block II, IIA, IIR and IIR-M satellites. Block IIF satellites are the next generation of GPS satellites and the first satellite is planned to be launched year 2008. [3].

2.2 Space Segment

GPS system requires a minimum of 24 satellites to operate [1]. However, currently there are 30 GPS satellites orbiting the earth [4]. Satellite orbit radius is 26 560 km and one orbit takes 11 hours 58 minutes, which is exactly $\frac{1}{2}$ sidereal day [1]. There are six different orbit planes, which all cross the equator at 55 degree inclination. Planes are equally spaced with a 60 degree separation at equator. See Figure 1 below [5].

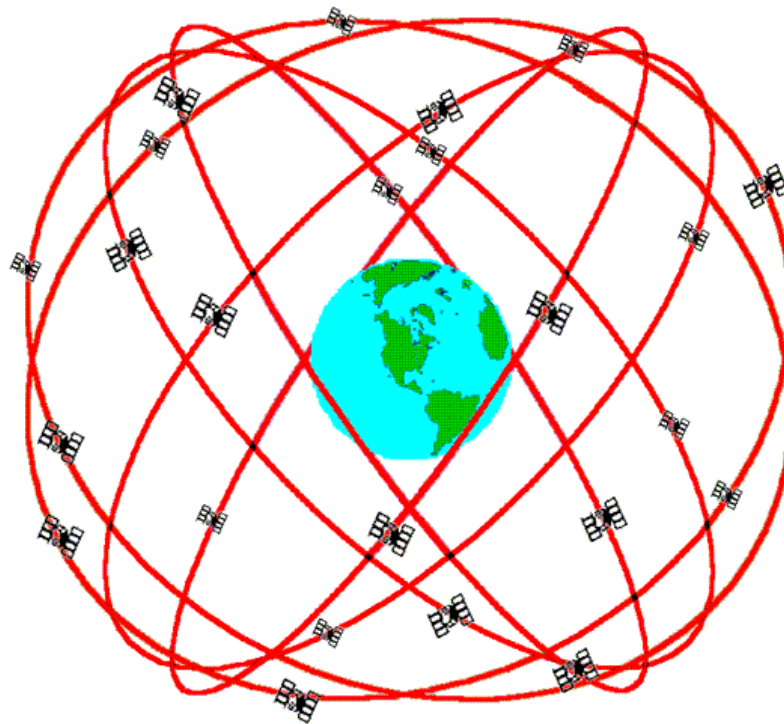


Figure 1. GPS Constellation

Communication between satellites and GPS receivers is one-way. GPS satellites send two different signals to GPS receivers. These signals are called L1 and L2. L1 is sent on carrier wave of 1575.42 MHz and L2 is sent on 1227.6 MHz. As satellite positioning is based on measuring time, clocks are very important. Satellite signals are generated using either cesium (older satellites) or rubidium clocks [1]. Each satellite broadcasts unique messages. In order to be able to use only two frequencies, signals are multiplexed using Code Division Multiple Access (CDMA) [2].

2.3 Control Segment

Control segment consists of five ground monitor stations, which are located in Colorado Springs, Diego Garcia, Ascension Island, Kwajalein and Hawaii. Data from monitor stations is collected to a master control station in Colorado Springs. Stations monitor satellite status, track and clock errors. Based on this data the master control station sends

navigation information to the satellites. Information is sent using three ground antennas in Diego Garcia, Ascension Island and Kwajalein [1] [3].

2.4 User Segment

Users can be divided into civil and military users. Military users can use an encrypted positioning signal called Precise (P)-code, where as civil users can use the Coarse/Acquisition (C/A)-code. A GPS receiver can be either single or dual frequency. A dual frequency receiver can use both L1 and L2 signal to achieve better accuracy when compared with single frequency receivers. As mentioned earlier, communication is one-way, which means that the receivers do not send any information to the satellites. More in depth information on GPS signals is in chapter 2.6 [1] .

2.5 Positioning

A GPS receiver measures the time it takes for the GPS signal to travel from a satellite to the receiver. Receiver's distance to the satellite can be calculated by multiplying the signals travel time with the speed of light. This distance is called *pseudorange*, pseudo denotes here that range is estimated and contains an error. When satellite's position and the range to the satellite are known the receiver is known to be on a sphere around the satellite. If a range to another known satellite can be measured, the receiver is known to be on a circle plane where the two spheres around these satellites intersect (See Figure 2.). When a distance to a third satellite is measured a third sphere intersects the circle in two points, where the lower point is the receiver location. This is shown in Figure 3. [1].

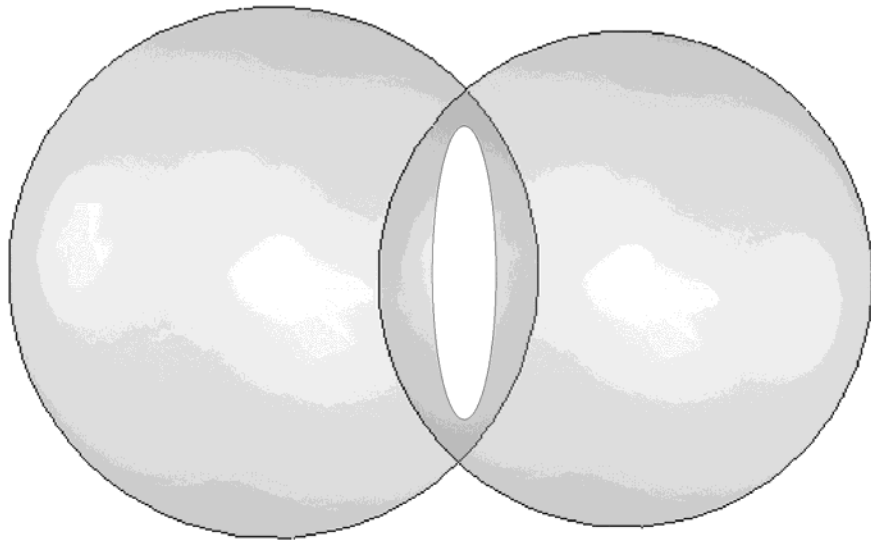


Figure 2. Receiver position with two satellites

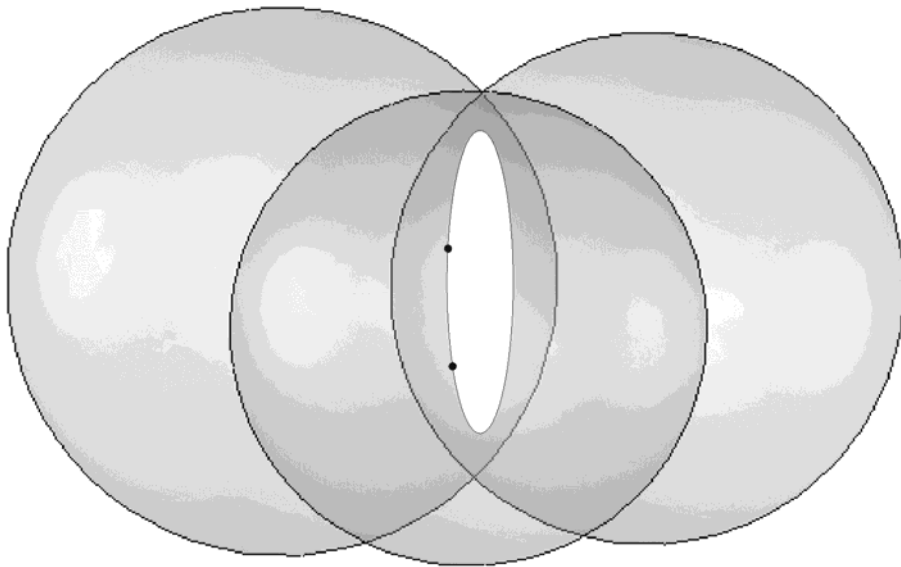


Figure 3. Receiver position with three satellites

In order to determine receiver's position, at least four pseudoranges to known satellite positions are required. Three pseudoranges are needed for the geometrical calculations as described above and the fourth is used to solve receiver's clock error. Receiver clocks are usually generated with less accurate crystal oscillators, where as the satellite clocks are generated by high accuracy atomic oscillators. Hence, fourth pseudorange is needed to

solve the error caused by the inaccurate receiver clock. Even though four satellites are enough for calculating the receiver position, usually a GPS receiver monitors all visible satellites in the sky. Additional satellites can be used to improve positioning accuracy [2]. The position accuracy for a single frequency C/A-code receiver has been specified to be better than 13 meters horizontally and 22 meters vertically. This means that 95 percent of all possible horizontal location measurements fall in to a circle that has a radius of 13 meters [2].

As noted in the beginning of this sub chapter, also satellite's position need to be known. Each GPS satellite sends unique *ephemeris* (i.e. satellite's track information) data, which can be used to calculate satellite position at a certain instant of time or *epoch* [6].

2.6 GPS Signal

As mentioned earlier, GPS satellites broadcast GPS signals on two different carrier frequencies L1 (1575.42 MHz) and L2 (1227.60 MHz). Both C/A-code and P-code are modulated into L1-signal and P-code is also modulated to L2 signal. Each satellite sends a unique P-code, which is used to identify each satellite. This identification is called Pseudo Random Noise (PRN) code [2]. In GPS there are 32 PRN codes for satellites and five for ground stations [1].

In addition to C/A- and P-code each satellite sends a unique navigation message. Navigation message is sent on 50 bit/s data rate and contains information for calculating satellite's position. The navigation data is contained in a 1500-bit frame, which is divided into five 300-bit subframes as shown below in Table 1 [2].

	bits 1-30	bits 31-60	bits 61-300
Subframe-1	TLM	HOW	GPS week number, satellite accuracy and health, satellite clock correction terms
Subframe-2	TLM	HOW	Satellite ephemeris
Subframe-3	TLM	HOW	Satellite ephemeris
Subframe-4	TLM	HOW	Almanac and health data for other satellites, special messages, satellite configuration flags, ionosphere and UTC data
Subframe-5	TLM	HOW	Almanac and health data for other satellites, almanac reference time and week number
	<- 300 bits, i.e. 6 seconds at 50 bit/s ->		

Table 1. Navigation Message

Each subframe is further divided into ten 30-bit words. A word contains 24 data bits and six parity bits for transmission error detection (see Figure 4). First word of each subframe is a telemetry (TLM) word followed by a handover word (HOW). TLM contains a fixed 8-bit preamble (10001011), which the receiver uses for locating the beginning of a subframe. Preamble is followed by data bits for authorized users (P-code receivers). HOW provides current GPS time of week and subframe ID [6].

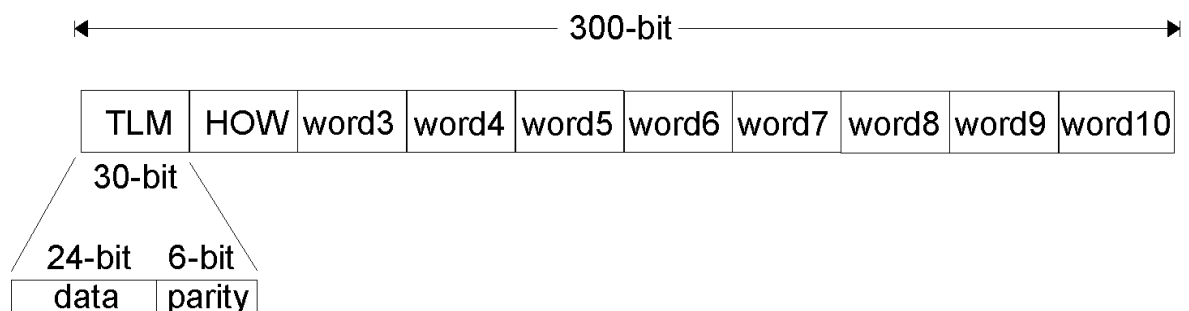


Figure 4. GPS Subframe

Subframe-1 words from three to ten contain GPS week number, satellites accuracy, satellites health and satellites clock correction terms. Week number is a sequential number of weeks where the counting has been started January 5, 1980. Week number rolls over every 1024 weeks. Satellite accuracy can be used to estimate the error in the pseudorange measured to the satellite. Satellite health data is used to indicate a malfunction in the satellite or that possibly inaccurate navigation data is being sent. Clock correction terms allow the user to estimate satellite's clock error due to oscillator bias, drift and aging [6]. Note that the receiver's clock error is common to all pseudorange measurements and can be resolved by measuring a fourth pseudorange as noted in chapter 2.5.

Subframes-2 and -3, words from three to ten contain satellites ephemeris data. Ephemeris data contains parameters that are needed to calculate the satellites location at a certain time (epoch) [2].

Subframe-4 has 25 different pages, which means that each time the entire frame is broadcasted frame four contents will be different. When the entire frame has been broadcasted 25 times the same pages will be sent again. Subframe 4 contains *almanac* data, ionosphere corrections and Coordinated Universal Time (UTC)-data. Almanac data is similar to ephemeris data, but coarser. It can be used to estimate the position of all GPS satellites. This way the information sent by just one of the satellites can be used to calculate an estimated position of all satellites. When the satellites position is known it is easier to start receiving the navigation signal from it. The ionosphere corrections are data which can be used to model the signal delay in the atmosphere (see chapter 2.7). UTC data is used for correlating the GPS time with UTC time, i.e. GPS satellites can be used for providing exact time to the user [6].

Subframe-5 is similar to subframe-4 and also contains 25 pages. The subframe contains almanac data and almanac reference time. Almanac reference time is used for calculating satellite positions using the almanac data [6].

2.7 Error Sources

As the GPS signal travels at the speed of light, one microsecond error in the measurement counts for 300 meters error for the pseudorange. When bearing this in mind, it is obvious that there will always be some (significant) magnitude of error in the positioning. Errors are introduced either in the satellite, in the atmosphere or in the receiver. Pseudorange error is a sum of all these individual errors. There are several causes for measurement errors in GPS positioning. Single frequency C/A-code receiver error sources, their standard deviation (1σ) and variance (2σ) are shown in Table 2 below. It should be noted that these are residual errors after the different corrections described in 2.6 have been applied [2].

Error Source	1σ Error (m)	2σ Error (m)
Satellite clock	1,1	1,21
Group delay	0,3	0,09
Satellite track	0,8	0,64
Ionosphere	7,0	49
Troposphere	0,2	0,04
Receiver noise and resolution	0,1	0,01
Multipath	0,2	0,04
Total	7,1	51,0

Table 2. GPS Error Sources

Even though the satellites have extremely accurate atomic clocks and their errors are corrected with the clock correction parameters provided in the navigation messages, there still remains some error. The clock correction parameters are a prediction of error curve over a certain period of time. The satellite clock errors are the residual left after the correction parameters have been applied. The residual error varies depending when the

correction parameters were uploaded to the satellite from the control segment. The error is smallest right after the parameters have been uploaded, which is typically done daily. On the other hand, the error is largest when 24 hours have passed since the previous upload [2].

Group delay error is present when using the C/A-code for calculating the pseudorange. It is caused by the fact that satellite clock correction parameters refer to P-code and the synchronization bias between these two signals cannot be completely removed [2].

Satellite ephemeris is sent to the satellite from the control segment. It is a curve fit of the predicted satellite ephemeris, therefore some error is introduced. The error is typically smaller when the receiver is around a vector from the centre of earth to the satellite and on the other hand, larger to other directions [2].

The largest pseudorange error is caused by the atmosphere's ionosphere layer. Ionosphere is located in the atmosphere at altitudes from 50 km to 2000 km. In ionosphere ultraviolet rays from the sun ionize gas molecules and release free electrons (sun storms). The amount of free electrons varies from time to time. These free electrons cause a dispersive delay to the GPS-signal. Dispersive means that the delay is dependent on the signal frequency, which is useful for dual frequency receivers as they can calculate the ionospheric delay. Single frequency receivers must model the ionospheric delay using the ionosphere data provided in the navigation message. Ionospheric delay is also highly dependent on the angle the signal passes through atmosphere. When the angle is low the signal will have to travel longer in the ionosphere and the delay will be larger. This is called the *obliquity factor* [7].

Troposphere is an atmosphere's layer located below the ionosphere. Troposphere is non-dispersive and is usually modeled as two different components: dry and wet. The dry component is responsible for approximately 90% of the tropospheric delay and it can be modeled very accurately. The wet component however is much more difficult to predict. As most of the delay is caused by the dry component the error introduced by tropospheric delay is relatively small [1].

There are three sources of error in the receiver: thermal noise, interference and multipath signals. In a modern receiver, thermal noise jitter and interference errors are typically in the magnitude of ten centimeters and therefore their effect to the positioning accuracy is quite small. Multipath errors are caused when the signal is reflected from for example nearby buildings or hills and the receiver receives a signal which is delayed by the reflected distance. It is also possible that the reflected signal distorts the phase of the direct signal and introduces an error [1].

The position error is determined by the pseudorange errors described above and satellite positions. The affect of satellite positions is called the *dilution of precision* (DOP). When the satellites are close to each other DOP is high and when the satellites are spread apart DOP is low. This is shown in Figure 5 and Figure 6. Actual receiver position is where the middle lines cross each other, but because of the error margins the position is measured to be somewhere in the grayed area. As it can be seen in the figures when satellites are closer to each other, the area (i.e. DOP) grows [2].

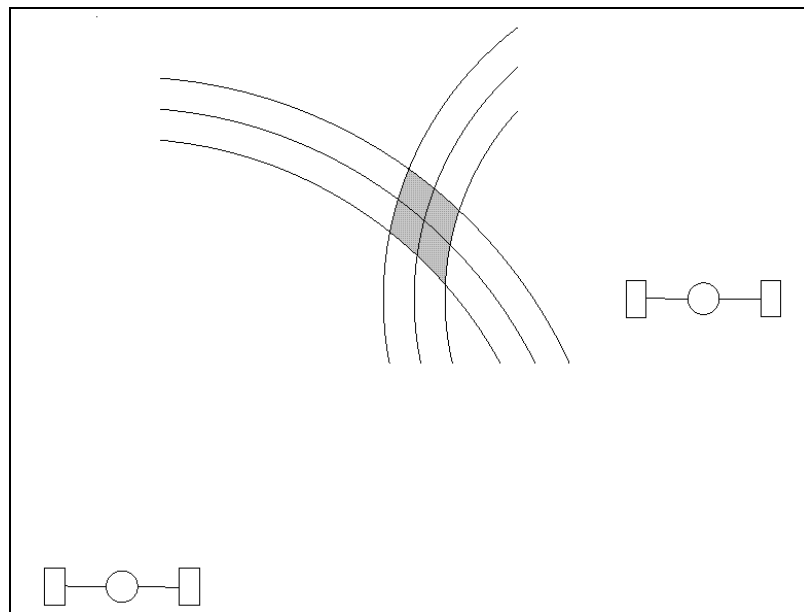


Figure 5. Low dilution of precision

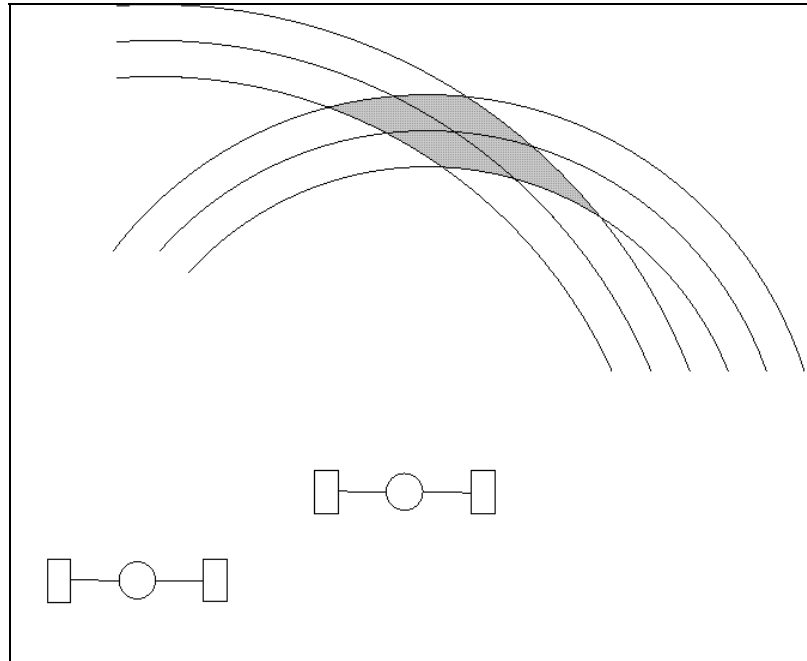


Figure 6. High dilution of precision

Receiver's DOP does not need to be calculated in real-time. It can also be calculated in advance from satellite ephemeris and estimated receiver position. There are several ways to present the DOP. In this research position DOP (PDOP) value is used, which represents the effect of satellite positions in three dimensions. An ideal DOP value is one and if the DOP is more than 8-10 it is considered poor for positioning purposes. Even though the satellites in the sky are in good geometric formation, it does not guarantee a good DOP value. Receiver's DOP value may suffer from obstacles that block the signal from one or more satellites [1].

3 European Geostationary Navigation Overlay Service (EGNOS)

EGNOS is an SBAS for GPS. EGNOS provides augmentation data for GPS receivers. When EGNOS data is combined with GPS data, the receiver can achieve more precise positioning. Furthermore, the augmentation data can be used to estimate positioning accuracy [2].

EGNOS is one of the regional SBAS implementations and is operational in Europe. Other SBAS implementations are Wide Area Augmentation System (WAAS) in North America, Multifunctional Transport Satellite (MTSAT) in Japan and the GPS and GEO Augmented Navigation (GAGAN) in India. WAAS is already operational, MTSAT is under implementation and GAGAN is under development [2].

The augmentation data is provided through satellites that are on geostationary orbit, which means that these satellites orbit earth over equator at the same speed as earth rotates. Hence, when looking from earth's surface the satellites are always at the same spot in the sky. These satellites are not part of the GPS-constellation described in 2.2, but are operating independently [8].

3.1 History

EGNOS is implemented by the so called European Tripartite Group, which consists of European Space Agency (ESA), European Commission and Eurocontrol. It is the first step in the European strategy on satellite navigation. The second step will be to implement an independent Global Navigation Satellite System – Galileo [9]. EGNOS design was started in 1997 and its implementation was started 1999. Implementation is mainly performed by Alcatel Space Industries under ESA contract [10]. EGNOS became operational in mid-2005 and is currently under testing, which means that it can be used for non-safety of life operations. EGNOS is expected to become fully operational during 2007 [9].

Main motivation for SBAS and EGNOS has been aeronautical applications. GPS does not provide such reliability and precision that it could be used for safety of life operations,

such as navigating airplanes. EGNOS has been designed to improve positioning precision and more importantly reliability and predictability, any failures will be detected in seconds and alternative navigation means can be used. This means that for example the EGNOS/GPS receiver of an airplane can detect when the satellite navigation is not performing adequately and use other means for navigation [10]. Although EGNOS has been mainly designed for aeronautical applications it is widely used for other applications, such as land vehicle or maritime navigation [9].

3.2 Principles of Differential GPS (DGPS)

SBAS systems are a subset of DGPS applications. DGPS is a method to improve positioning using reference stations with known positions. The reference stations typically have dual frequency receivers so they can measure the ionospheric delay. As the reference station position is known, it is also possible to estimate ephemeris and clock error for each visible satellite. A reference station can also measure satellite's health. If the GPS satellite is constantly sending misleading information, it can be flagged as "don't use" [2].

The data from the reference station or stations is transmitted to DGPS receivers. The receiver is then able to improve positioning accuracy by combining DGPS data with the data it receives from the GPS satellites. DGPS data can for example be sent from ground based antennas or as in the case of SBAS from satellites [2].

3.3 EGNOS Architecture

EGNOS consists of four segments: ground, space, user and support segments. These segments and their main parts are shown in Figure 7, excluding support segment [8]. Following chapters explain each segment's purpose and main parts.

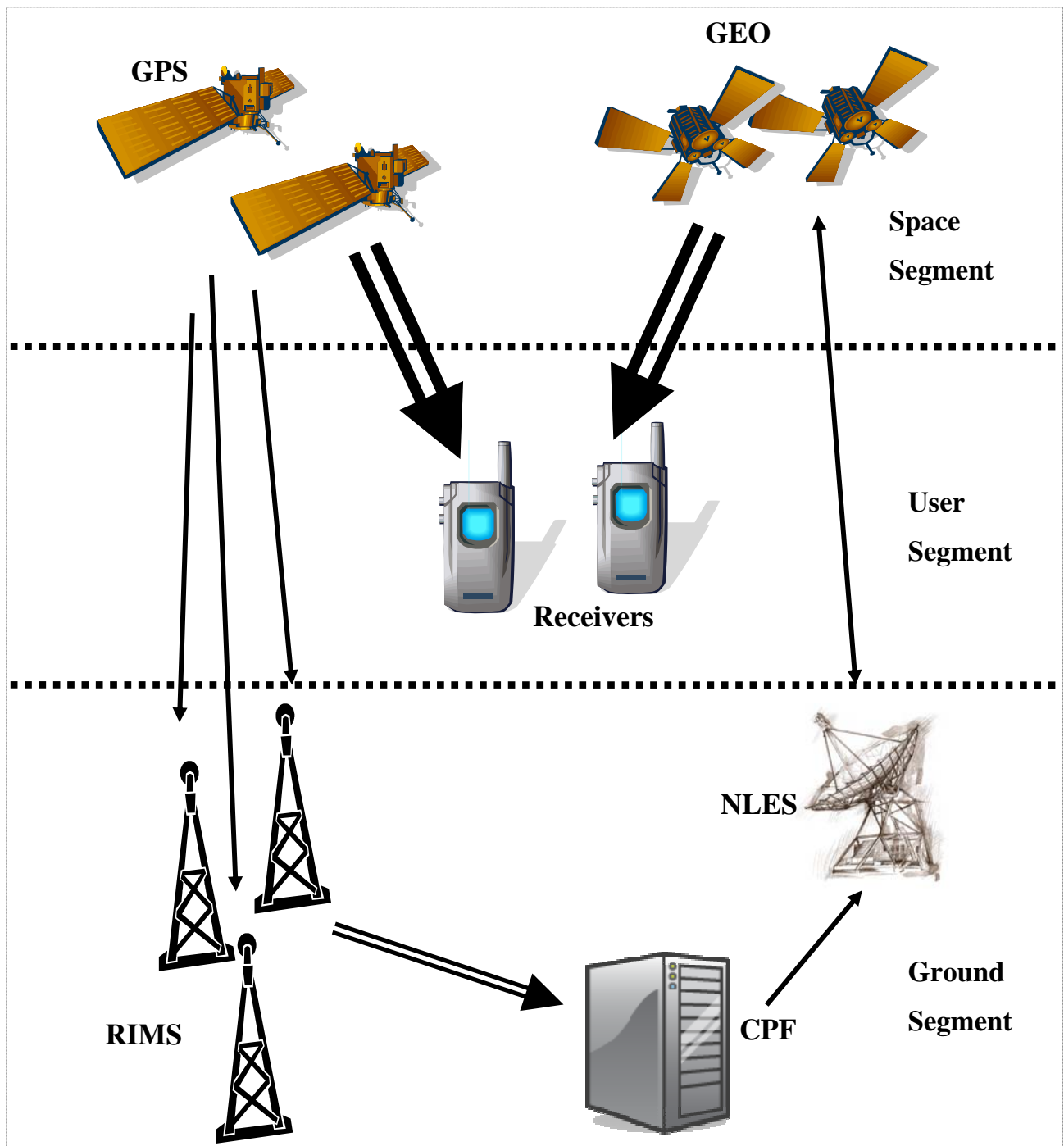


Figure 7. EGNOS System Architecture

3.3.1 Ground Segment

Ground segment consists of Ranging and Integrity Monitoring Stations (RIMS), Central Positioning Facility (CPF), Navigation Land Earth Stations (NLES), Central Control Facility (CCF) and EGNOS Wide Area Network (EWAN) [8] .

Each RIMS is equipped with several GPS receivers for performing measurements on GPS satellites in view. Position of each station is very precisely known, which means that they can measure GPS satellite errors as described in 3.2. Currently there are 31 RIMS spread around Europe and three RIMS in Canada, South Africa and French Guiana [8].

Data collected in RIMS is sent to CPF. CPF combines this data, in order to create correction data for the user segment. There are five identical CPFs in different locations in Europe. Only four of them are required for full operation of EGNOS and the fifth can be used as a backup [8].

NLES receive the correction data from CPF. Correction data is transformed into GPS-like signal and uploaded to geostationary satellites. There are six NLES stations; two for each satellite (see 3.3.3). This means that there are three NLES for redundancy [8].

CCF controls the entire EGNOS ground segment. There are four CCFs, where three are for backup. The different parts of ground segment are connected together with EWAN, which is a high speed data network with high redundancy [8].

3.3.2 User Segment

An EGNOS receiver is a slightly modified version of a GPS receiver. Minor hardware modifications are required and a modified software to utilize the EGNOS corrections. An example implementation of EGNOS receiver software is described in chapter 5. All SBAS implementations mentioned in the beginning of chapter 3 are fully compatible. This means that for example an EGNOS receiver also works in WAAS operation area and vice versa [2].

3.3.3 Space Segment

EGNOS Space segment consists of three geostationary satellites, referred as GEO. These are Inmarsat-3 AOR-E, Inmarsat-3 IOR-W and ESA-Artemis. AOR-E is over Atlantic Ocean, IOR-W is over Indian Ocean and ESA-Artemis is over Africa. Each satellite sends EGNOS-signal on GPS L1 frequency. The signal has been designed to minimize hardware modifications to standard GPS receivers. EGNOS signal is modulated similarly to GPS,

but the EGNOS data rate is 250 bit/s and differs from GPS data rate of 50 bit/s. EGNOS satellites also transmit regular GPS signal and can be used as additional GPS satellites for positioning purposes [2].

3.4 EGNOS Messages

SBAS signal has been standardized by Radio Technical Commission for Aeronautics (RTCA) in reference [11]. Unless otherwise stated, the information in this chapter and subchapters is based on the RTCA standard.

SBAS message structure is shown in Figure 8 below. Each message starts with 8-bit preamble for synchronization. 6-bit message type field allows 64 different message types. However currently there are only 20 message types defined. Data field length is 212 bits and its contents depend on the message type. At the end of each message there are 24-bits for message Cyclic Redundancy Check (CRC).

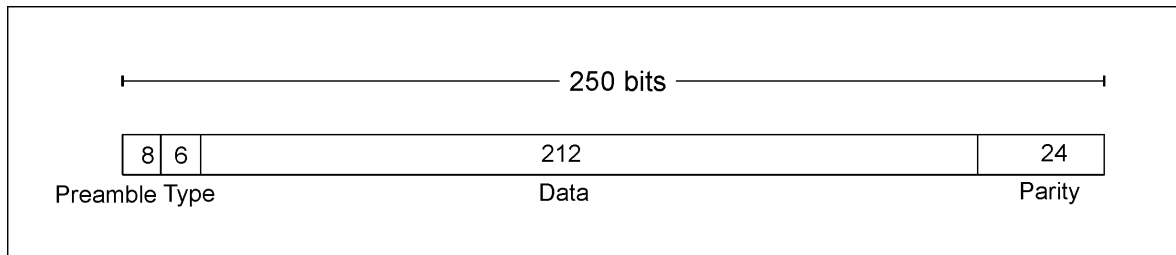


Figure 8. SBAS Message Structure

Table 3 shows all defined SBAS message types and the information they contain. Following chapters describe each message in detail, with focus on the important issues for this research. Exact bit-level description for each message type can be found in [11].

Type	Contents
0	Don't use for safety applications
1	PRN Mask Assignment
2-5	Fast corrections
6	Integrity information
7	Fast Corrections degradation factor
9	GEO navigation message
10	Degradation parameters
12	SBAS Network time /UTC time offset parameters
17	GEO satellite almanacs
18	Ionospheric grid point masks
24	Mixed fast corrections/long-term satellite error corrections
25	Long term satellite error corrections
26	Ionospheric delay corrections
27	SBAS service message
28	Clock-ephemeris covariance matrix message
62	Internal test message
63	Null message

Table 3. SBAS Message Types

3.4.1 Message Type 0

Message type 0 indicates that SBAS signal from this satellite should not be used for safety of life applications. This message is broadcast mainly during system testing phase, which at the time of writing is in action for EGNOS. Message data may either be all zeroes or data of message type 2. If message contains data, it can be used in non-safety of life applications.

3.4.2 Message Type 1

Message type 1 contains 210 bits for PRN mask and two bits for Issue Of Data PRN (IODP). PRN mask is used to define which satellites are augmented in the following augmentation messages. A mask bit that is set to one indicates that corresponding satellite is being augmented. As mentioned in 2.6 there are 37 PRN codes for GPS rest of the 210 bits are reserved for GEO satellites, GLONASS satellites and future use. GLONASS is a Russian satellite positioning system. Maximum of 51 satellites are allowed to be defined as augmented in the PRN mask. PRN assignments to mask bits are defined in [11].

IODP bits identify the mask being used. When a new PRN mask is issued old and new masks can be distinguished with IODP (see following chapters).

3.4.3 Message Types 2-5

Messages 2-5 are called fast correction messages. They provide data to correct satellite clock errors and data to estimate pseudorange error variance. Message type 2 contains data for the first 13 satellites defined in the PRN mask (message type 1). Type 3 message contains data for the next 13 PRN mask satellites (14-26). Type 4 message is for satellites 26-39 and type 5 for satellites 40-51. If the mask contains less than 40 satellites, message type 5 is not broadcast. Each message starts with IODP to correlate the correction message to a PRN mask.

Each satellite's fast correction is a signed 12-bit number with a resolution of 0.125 meters. The fast correction is added to a GPS pseudorange measurement. Additionally there is a 4-bit User Differential Range Error Indicator (UDREI), which can be transformed into a

variance or standard deviation for error estimation. UDREI indicates the combined accuracy of both fast corrections and long term error corrections (see also 3.4.12).

3.4.4 Message Type 6

Message type 6 contains UDREI values for all satellites defined in the PRN mask. Same information is also transmitted in messages 2-5, but message 6 allows quick update on UDREI values. If quick UDREI updates are not needed, message type 6 does not need to be broadcast.

3.4.5 Message Type 7

Message type 7 includes fast correction degradation factors, i.e. how the fast corrections change over time. Message contains degradation factors for all satellites defined in the PRN mask. The degradation factors are especially important during for example flight navigation. If a fast correction message is lost during critical phase of a flight, the correction can be estimated.

The fast correction degradation is provided with a 4-bit degradation factor indicator for all satellites defined in the PRN mask of message type 1. This indicator is used in the fast correction calculation (see 3.5.1.). The degradation factor also determines a time-out period for fast correction messages. Time-out periods for fast correction messages may vary between 6 to 60 seconds. If the latest fast correction message is older than the time-out period, it is no longer valid and should not be used. In normal situations fast correction messages are provided in such way that there are valid corrections always available. However if messages are for some reason lost or delayed, it is possible that the receiver does not receive new fast correction messages in time.

3.4.6 Message Type 9

Message type 9 contains GEO satellite navigation message. GEO satellites are not part GPS, and their navigation data is therefore not available through other means than SBAS. GEO navigation message contains GEO satellite's ephemeris.

3.4.7 Message Type 10

Message type 10 contains degradation factors for long term corrections, ionospheric corrections and GEO satellite navigation messages. Message is used similarly to message type 7.

3.4.8 Message Type 12

Message type 12 contains SBAS network time and offset from network time to Coordinated Universal Time (UTC). The data provided in the message is similar to GPS data mentioned in chapter 2.6.

3.4.9 Message Type 17

Message type 17 contains almanac data for up to three GEO satellites. As mentioned in 3.4.6 GEO satellites are not part of the GPS constellation and the navigation and almanac data has to be transmitted through SBAS.

3.4.10 Message Type 18

Ionospheric delay corrections are broadcast as delay estimates at predefined grid points. These grid points are called Ionospheric Grid Points (IGPs). There are 2192 grid points around the globe. These points have been divided into 11 different bands. A message type 18 contains a mask for one band, informing the receiver which grid points in that band are being monitored.

Message contains 4-bit number of bands being broadcast, 4-bit band number, two bit Issue Of Data Ionosphere (IODI) and 201-bit IGP mask. SBAS does not have to broadcast IGP information for all 11 bands. When receiver is informed how many bands are being broadcast, it can determine when it has received all IGP information. Band number indicates, which band's mask is being broadcast in this message. IODI bits identify the mask being used. When a new IGP mask is issued old and new masks can be distinguished with IODI. The actual mask is 201 bits long, where a bit set to one indicates that ionospheric correction is available for that IGP.

3.4.11 Message Type 24

If a fast corrections message (message type 2-5) would consist only six or less satellites its contents may be put into a message type 24. Message type 24 combines fast corrections and long term corrections into one message. First half of the message contains fast corrections and second half contains long term corrections. Message contents are similar to message types 2-5 and 25.

3.4.12 Message Type 25

Message type 25 provides corrections to slow varying satellite ephemeris and clock errors. Message is divided into two 106-bit halves. Each half may contain corrections for one or two satellites. Both halves have identical structure. Therefore from here after only one half's contents are being described. First bit in the half is called velocity code. If it is set to zero, the half contains corrections for two satellites. If the bit is set to one the half contains corrections for only one satellite.

When velocity code is set to zero the half contains only clock offset and position component estimate. Otherwise when velocity code is one, the half includes three additional parameters: clock drift, velocity component estimates and time of day applicability. Clock drift and clock offset parameters are used to correct satellites slow varying clock errors. Position and velocity component estimates are used to correct satellites position vector error (i.e. ephemeris error). Time of day applicability is needed when calculating corrections with clock drift and velocity component estimates (see 3.5.2). Depending on the clock and ephemeris error sometimes it is enough to correct the errors with a message where velocity code is zero. On the other hand, sometimes additional parameters are needed and the velocity code is set to one.

In addition to parameters described above satellite's PRN mask number is given to indicate which satellite is being corrected. Furthermore GPS Issue Of Data (IOD) and IODP are given. IOD and IODP bits identify the masks PRN mask number refers to. Hence when a new IOD or IODP mask is issued, PRN mask number can always be related to correct

satellite. Similarly to fast correction messages long term correction messages also have a time-out period. The time-out period for long term corrections is 360 seconds.

3.4.13 Message Type 26

Message type 26 contains ionospheric delay corrections for IGPs defined in the message type 18 (see 3.4.10). The message contains band number, block ID, IODI, 15 IGP delay estimates and 15 Grid Ionospheric Vertical Error Indicators (GIVEI). As mentioned in 3.4.10 IGPs have been divided into 11 different bands. Each band is further divided into blocks, where each block contains 15 IGPs. With band number, block ID and IODI the receiver is able to determine which IGP delays are reported in the current message.

IGP delay estimates are provided as 9-bit unsigned numbers, which represents the delay in meters. Resolution is 0.125 meters per bit, which results to a delay of 0 to 63.875 meters. This represents the delay in pseudorange measurement caused by the ionosphere on GPS L1 signal. Additionally there is a 4-bit GIVEI, which can be transformed into a variance or standard deviation for error estimation. IGP delay information also has a time-out period which is 600 seconds. If the information for an IGP is older than 600 seconds it is no longer considered valid and should not be used for corrections.

3.4.14 Message Type 27

Message type 27 is called the SBAS service message and it can be used to multiply the User Differential Range Error (UDRE) given by the UDREI in messages 2-6 or 24. However it is not used in EGNOS and is therefore not in this thesis' scope [12].

3.4.15 Message Type 28

Message type 28 contains a clock ephemeris covariance matrix, which can be used to improve the UDRE estimation. However the message is not used in EGNOS and is therefore not in this thesis' scope [12].

3.4.16 Message Type 62

Message type 62 is an internal test message and is disregarded by the receiver.

3.4.17 Message Type 63

Message type 63 is a null message, which is sent if there is no other message to be sent. Receivers disregard this message.

3.5 Applying EGNOS Corrections

There are three types of corrections provided in the SBAS messages. These are fast corrections, long term satellite error corrections and ionospheric delay corrections. Following chapters describe how these corrections are applied to the pseudorange measurements performed by a GPS receiver. This chapter is based on reference [11].

3.5.1 Fast Corrections

Using the information in messages 2-5 and 7 the corrected pseudorange ($PR_{corrected}$) for a satellite is calculated as shown in (1).

$$PR_{corrected}(t) = PR_{measured}(t) + PRC(t_{of}) + RRC(t_{of}) * (t - t_{of}) \quad (1)$$

If the satellite's fast correction degradation factor indicator (see 3.4.5) is zero, Range Rate Correction (RRC) is also zero. If the indicator is not zero RRC is calculated as shown in (2).

$$RRC(t_{of}) = \frac{PRC_{current} - PRC_{previous}}{\Delta t} \quad (2)$$

The coefficients in (1) and (2) are as follows:

$PR_{measured}$ = Pseudorange measured by a GPS receiver

$PRC_{current}$ = the most recent fast correction (same as $PRC(t_{of})$)

t = current time

$PRC_{previous}$ = previous fast correction

Δt = $t_{of} - t_{of,previous}$

t_{of} = time of applicability of the most recent fast correction

$t_{of,previous}$ = time of applicability of the $PRC_{previous}$

Above mentioned time of applicability is the time when the fast correction message is sent.

3.5.2 Long Term Satellite Error Corrections

With the information provided in messages 24 and 25 satellite's clock time error estimate ($\delta\Delta t_{SV}$) at a time of day (t_k) is calculated as shown in (3).

$$\delta\Delta t_{SV}(t_k) = \delta a_{f0} + \delta a_{f1}(t_k - t_0) \quad (3)$$

The rest of the coefficients in (3) are as follows:

δa_{f0} = Clock offset error correction

δa_{f1} = Clock drift error correction

t_0 = Time of day applicability

If the clock drift error correction has not been defined (velocity code = 0) for the satellite in question, it set to be zero.

Result of equation (3) is added to GPS space vehicle PRN code phase time offset (Δt_{sv}), which is part of GPS positioning calculations. Space vehicle PRN code phase time offset has been defined in reference [6].

Position error correction vector is the sum of position component error estimates and velocity component estimates. Furthermore, velocity component is multiplied by the difference between time of day and time of day applicability (see (4)). If the velocity

component estimates have not been defined (velocity code = 0) for the satellite in question, they are set to be zero.

$$\begin{bmatrix} \delta x_k \\ \delta y_k \\ \delta z_k \end{bmatrix} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} + \begin{bmatrix} \delta \dot{x} \\ \delta \dot{y} \\ \delta \dot{z} \end{bmatrix} (t_k - t_0) \quad (4)$$

Resulting position error correction vector is added satellite's coordinate vector, which is calculated during GPS positioning, as defined in reference [6].

3.5.3 Ionospheric Delay Corrections

In messages 18 and 26 the receiver receives a grid of points, where the ionospheric delay has been defined. Based on this grid the receiver then interpolates a delay value for each satellite in its visibility. First the receiver must determine the points where signals from each satellite have pierced the ionosphere. For piercing point determination the ionosphere is modeled as a thin layer 350 km above earth's surface. The latitude of the piercing point (ϕ_{pp}) in radians can be calculated as shown in (5).

$$\phi_{pp} = \sin^{-1} (\sin \phi_u \cos \Psi_{pp} + \cos \phi_u \sin \Psi_{pp} \cos A) \quad (5)$$

Ψ_{pp} is the earth's central angle between the receiver and pierce point and it can be calculated as shown in (6). Figure 9 illustrates the geometry of the pierce point calculation.

$$\Psi_{pp} = \frac{\pi}{2} - E - \sin^{-1} \left(\frac{R_e}{R_e + h_I} \cos E \right) \quad (6)$$

The coefficients in (5) and (6) are as follows:

ϕ_u = Receiver latitude

A = Satellite's azimuth angle

E = Satellite's elevation angle

R_e = Earth's radius (in this case 6378.1363 km)

h_I = Height of the ionosphere (350 km)

Azimuth angle is the direction where the satellite is. Zero degree is north and angle grows clock-wise. Elevation angle is the angle between local-tangent-plane and the satellite.

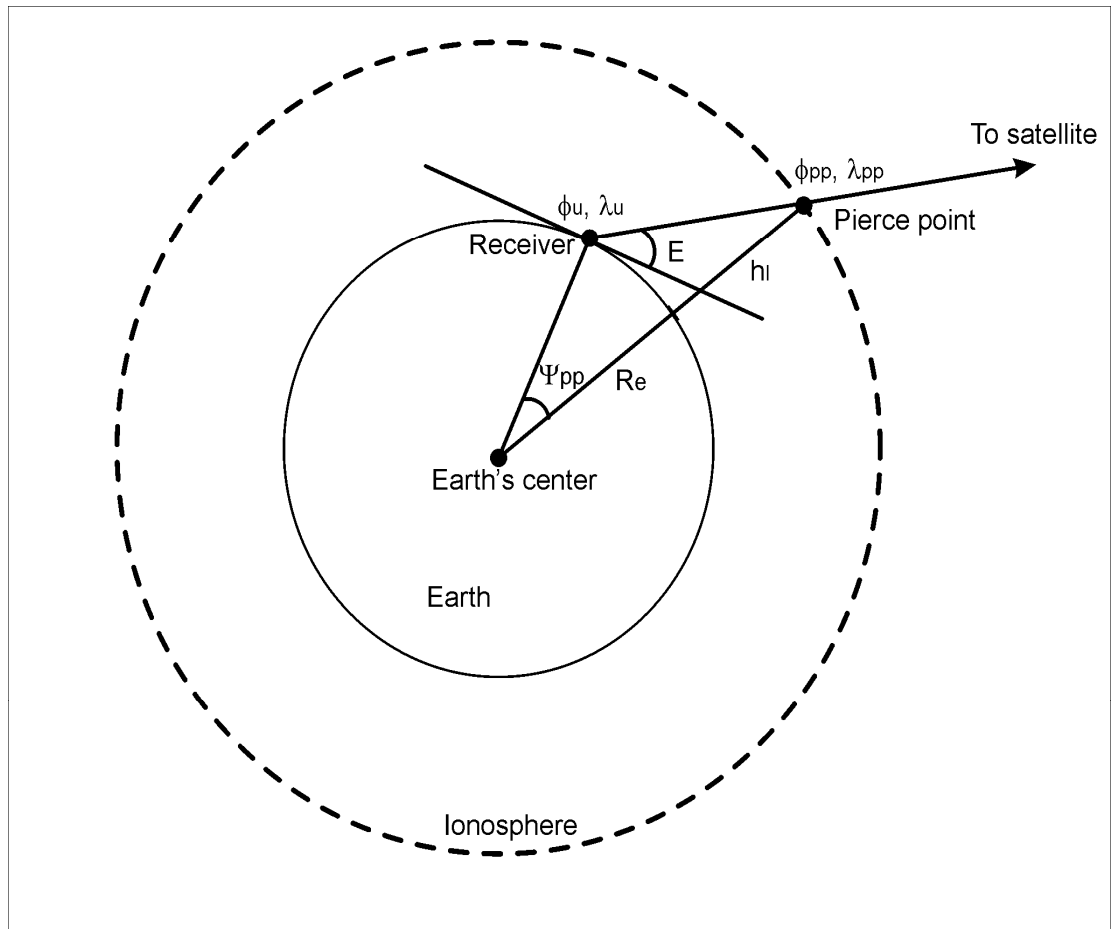


Figure 9. Pierce Point Geometry

The longitude of the pierce point (λ_{pp}) is calculated according to equation (9) if condition (7) or (8) is met:

$$(\phi_u > 70^\circ) \cap \left[\tan \Psi_{pp} \cos A > \tan \left(\frac{\pi}{2} - \phi_u \right) \right] \quad (7)$$

$$(\phi_u > -70^\circ) \cap \left[-\tan \Psi_{pp} \cos A > \tan \left(\frac{\pi}{2} - \phi_u \right) \right] \quad (8)$$

$$\lambda_{pp} = \lambda_u + \pi - \sin^{-1} \left(\frac{\sin \Psi_{pp} \sin A}{\cos \phi_{pp}} \right) \quad (9)$$

If neither condition (7) nor (8) is met, pierce point longitude is calculated according to equation (10).

$$\lambda_{pp} = \lambda_u + \sin^{-1} \left(\frac{\sin \Psi_{pp} \sin A}{\cos \phi_{pp}} \right) \quad (10)$$

When the pierce point location has been calculated, grid points around the pierce points are selected and the delay at the pierce point is interpolated. Grid point selection routine depends on the data available and the pierce point delay interpolation can be performed from three or four grid points. Further details on grid point selection and interpolation can be found in reference [11].

The delay at grid points is vertical delay, which means that it is the ionospheric delay for a GPS L1 signal piercing ionosphere perpendicularly. Similarly the interpolated delay at the pierce point is vertical delay. When the GPS signal pierces ionosphere in a non-perpendicular angle, obliquity factor must be taken into account (see 2.7). Obliquity factor (F_{pp}) is calculated as shown in equation (11).

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_f} \right)^2 \right]^{-\frac{1}{2}} \quad (11)$$

The vertical delay at a pierce point is multiplied by the obliquity factor and the result is subtracted from the GPS measured pseudorange.

3.5.4 Tropospheric Model

SBAS does not provide any corrections for tropospheric delay; however reference [11] provides a model for estimating the delay. The model uses receiver's height, elevation angle and five meteorological parameters to calculate an estimated delay. The meteorological parameters are pressure (P), temperature (T), water vapour pressure (e), temperature lapse rate (β) and water vapour lapse rate (λ). These parameters are estimated based on the day of year and receiver latitude.

For each meteorological parameter an average value (ξ_0) at receiver latitude (ϕ) is calculated according to equation (12). Similarly seasonal variation values ($\Delta\xi$) for the meteorological parameters are calculated as presented in equation (13).

$$\xi_0(\phi) = \xi_0(\phi_i) + [\xi_0(\phi_{i+1}) - \xi_0(\phi_i)] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)} \quad (12)$$

$$\Delta\xi(\phi) = \Delta\xi_0(\phi_i) + [\Delta\xi_0(\phi_{i+1}) - \Delta\xi_0(\phi_i)] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)} \quad (13)$$

The average values and seasonal variation values in equations (12) and (13) are calculated using predefined values at five given latitudes. These values and latitudes are shown in Table 4 and Table 5. Calculation for the average values and seasonal variations is done using two latitudes (ϕ_i and ϕ_{i+1}) out of the five given latitudes. The two latitudes are the latitudes closest to the receiver. If the receiver latitude is less than 15 degrees or more than 75 degrees, values for ξ_0 and $\Delta\xi$ are taken directly from the tables.

Latitude [°]	P ₀ [mbar]	T ₀ [K]	e ₀ [mbar]	β ₀ [K/m]	λ ₀ [°]
15° or less	1013.25	299.65	26.31	6.30e-3	2.77
30°	1017.25	294.15	21.79	6.05e-3	3.15
45°	1015.75	283.15	11.66	5.58e-3	2.57
60°	1011.75	272.15	6.78	5.39e-3	1.81
75° or more	1013.00	263.65	4.11	4.53e-3	1.55

Table 4. Average Meteorological Parameters

Latitude [°]	P ₀ [mbar]	T ₀ [K]	e ₀ [mbar]	β ₀ [K/m]	λ ₀ [°]
15° or less	0.00	0.00	0.00	0.00	0.00
30°	-3.75	7.00	8.85	0.25e-3	0.33
45°	-2.25	11.00	7.24	0.32e-3	0.46
60°	-1.75	15.00	5.36	0.81e-3	0.74
75° or more	-0.50	14.50	3.39	0.62e-3	0.30

Table 5. Seasonal Variation for the Meteorological Parameters

When the average and seasonal variation values at receiver latitude are known, the day of year (D) is used to calculate estimated meteorological values at current time of year. This is shown in equation (14).

$$\xi(\phi, D) = \xi_0(\phi) + \Delta\xi(\phi) \cdot \cos\left(\frac{2\pi(D - D_{min})}{365.25}\right) \quad (14)$$

Coefficient D_{min} in equation (14) equals 28 for northern latitudes and 211 for southern latitudes.

The meteorological parameters are used to calculate vertical delays at zero receiver altitude. The delays for the troposphere's dry component (z_{hyd}) and wet component (z_{wet}) are separately calculated as shown in equations (15) and (16). See also chapter 2.7.

$$z_{hyd} = \frac{10^{-6} k_1 R_d P}{g_m} \quad (15)$$

$$z_{wet} = \frac{10^{-6} k_2 R_d}{g_m (\lambda + 1) - \beta R_d} \cdot \frac{e}{T} \quad (16)$$

The coefficients in equations (15) and (16) are:

$$k_1 = 77.604 \text{ K/mbar}$$

$$k_2 = 382000 \text{ K}^2/\text{mbar}$$

$$R_d = 287.054 \text{ J/kg/K}$$

$$g_m = 9.784 \text{ m/s}^2$$

z_{hyd} and z_{wet} are used to calculate the vertical delays for dry (d_{hyd}) and wet component (d_{wet}) at receiver's height (H). Height is expressed in meters above mean sea level. This is shown equations (17) and (18).

$$d_{hyd} = \left(1 - \frac{\beta H}{T}\right)^{\frac{g}{R_d \beta}} \cdot z_{hyd} \quad (17)$$

$$d_{wet} = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1)g}{R_d \beta} - 1} \cdot z_{wet} \quad (18)$$

Coefficient g in equations (17) and (18) equals 9.80655 m/s^2 .

The tropospheric obliquity factor (m) for satellites with elevation (El_i) more than 5 degrees is calculated according to equation (19).

$$m(EI_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(EI_i)}} \quad (19)$$

Finally the tropospheric delay (TC_i) is calculated by adding the wet and dry delays and multiplying the result with obliquity factor. This is shown in equation (20). The resulting tropospheric delay is subtracted from a pseudorange measured by a GPS receiver.

$$TC_i = (d_{hyd} + d_{wet}) \cdot m(EI_i) \quad (20)$$

3.6 SISNeT

In chapter 3.3.2 it was mentioned that both software and hardware modifications are required for receiving SBAS corrections from GEO-satellites. However, in Europe ESA provides an alternative method to obtain EGNOS messages. In addition to GEO satellite signal, ESA provides the EGNOS messages through internet with a service called SISNeT [13].

SISNeT service can be used as an alternative to GEO satellites and provides a way to receive EGNOS corrections without any hardware modifications. Furthermore, as GEO satellites are over equator their signal is often hard to catch in latitudes further north (or south), as for example in Finland. SISNeT data rate is less than one Kbit/s, which makes it ideal for slow mobile terminal data connections [14].

3.6.1 SISNeT Architecture

SISNeT architecture consists of an EGNOS receiver, SISNeT server, and SISNeT client. EGNOS receiver is connected to all three EGNOS satellites and receives the augmentation messages in real-time. These messages are sent to the SISNeT data server. The server compresses the EGNOS messages using SISNeT Compression Algorithm (SINCA) and encapsulates the compressed messages into SISNeT messages. SISNeT messages are sent with Data Server to Data Client (DS2DC) protocol, which is further encapsulated into Transmission Control Protocol/Internet Protocol (TCP/IP) packets. SISNeT messages can be received with a DS2DC client, which connects to the data server via internet. The client

decompresses the SINCA compression and processes the EGNOS messages. SISNeT architecture is shown in Figure 10 [14].

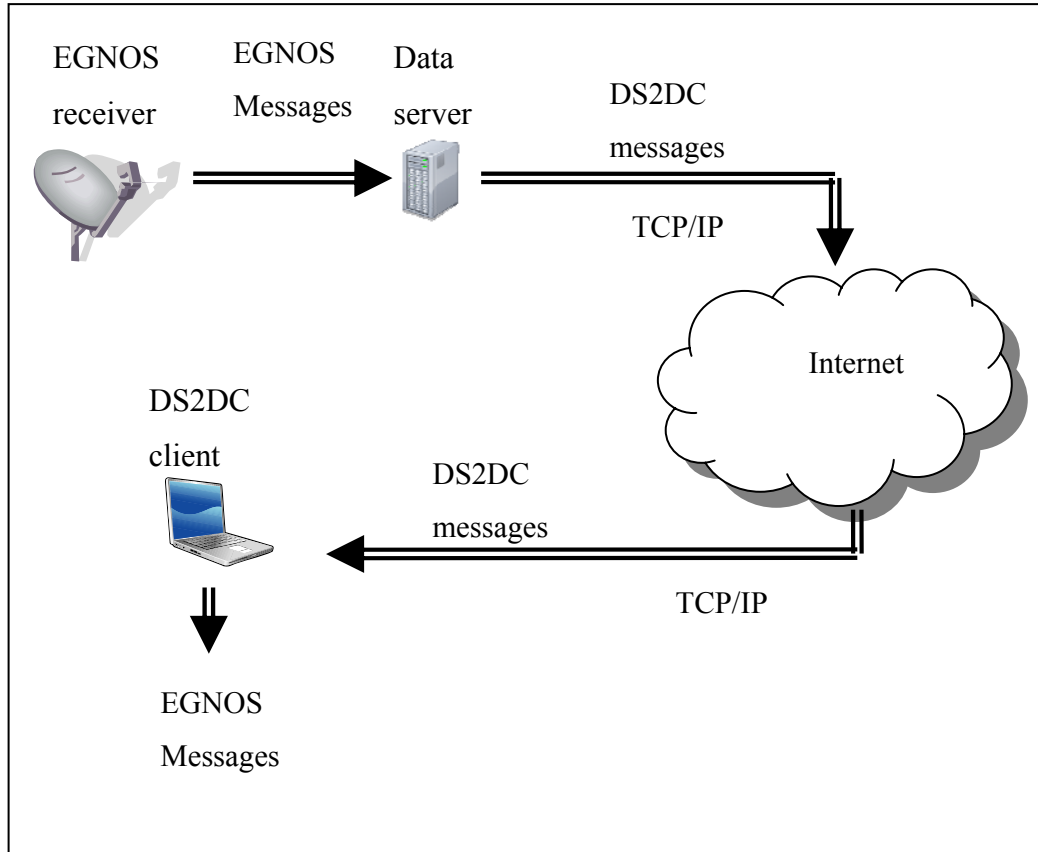


Figure 10. SISNeT Architecture

3.6.2 DS2DC Protocol

DS2DC protocol is based on ASCII messages, which are sent in TCP packets. The messages are composed of text fields separated by commas. First text field is always the name of the message type. Message end is denoted by Line Feed (LF) or Carriage Return (CR) and LF. Structure of DS2DC message is shown in Figure 11 [14].

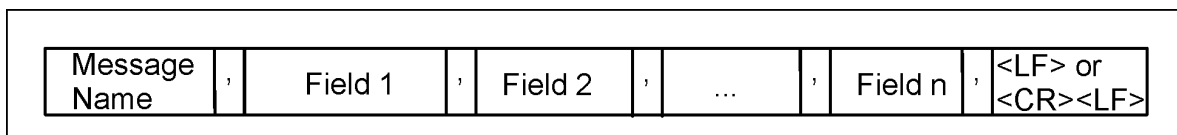


Figure 11. DS2DC message

There are two types of messages in DS2DC protocol; request and response messages. Request messages are sent from DS2DC client to data server and response messages are responses from the data server to DS2DC client. Response message names always start with an asterisk. Communication with the data server is always initiated with authentication, where the client provides the server a username and a password. At the time of writing, user names and passwords are provided free of charge by ESA. After successful client authentication, there are two alternative ways for communicating: The client may either request every second for the most recent EGNOS message or alternatively the client may request the server to automatically send the most recent message every second. The most important SISNeT messages, along with their purpose and contents are shown in Table 6 [14].

Message Name	Purpose	Fields
AUTH	Request message, which is sent as a first message when connecting to data server. Message provides user name and password. Successful authorization is responded with *AUTH message.	Username, password and optional field "q" for quick initialization.
*AUTH	Response to AUTH message	None.
MSG	Request for most recent EGNOS message.	None
*MSG	Response to MSG message.	GPS week, GPS time and SINCA compressed EGNOS message.
START	Request to start receiving *MSG messages continuously every second.	None.
*START	Response to START message.	None.
STOP	Request to stop receiving *MSG messages continuously.	None.
*STOP	Response to STOP message.	None.
*ERR	Response to an erroneous request.	Error code and error message.

Table 6. SISNeT Messages

3.6.3 SINCA Compression Algorithm

SINCA compression algorithm is a very simple compression method for EGNOS messages sent with DS2DC protocol. There are often repeating parts in EGNOS messages, which

can be compressed with SINCA. If a character is repeated 4 to 15 times the repeating part is replaced by the repeating character, "|" –character and a hexadecimal character representing number of repeats. Similarly if a character is repeated more than 15 times it is replaced by the repeating character, "/" –character and two hexadecimal characters representing number of repeats. For example string "AAAA AAAA AAA" would be replaced by "A|B" and string "2222 2222 2222 2222 2222" would be replaced by "2/14" [14].

4 Terrestrial Trunked Radio (TETRA)

TETRA is a digital mobile radio standard. TETRA has been defined by European Telecommunications Standards Institute (ETSI). It is targeted for professional mobile radio users such as public safety, transportation, government, military etc. Standard defines the network and terminal equipment interfaces to such extent that interoperability between different vendors equipment can be guaranteed [15].

4.1 Architecture

TETRA standard does not define an operating frequency, but it has been designed to operate in the frequency range of 300 MHz to 1000 MHz. This means that TETRA networks in different countries operate at different frequencies. In Europe, public safety and security forces use 380 MHz to 385 MHz and 390 MHz to 395 MHz frequency bands. For non-emergency users the bands allocated to TETRA differ from country to country, but bands 410 to 430 MHz and 450 MHz to 470 MHz are mainly used. Outside Europe, frequency bands around 400 MHz and 800 MHz are commonly used [16].

Within the operating band, carrier signal spacing is 25 KHz and each 25 KHz carrier includes four time division multiplexed channels. This means that TETRA is very frequency efficient if compared to for example Global System for Mobile communications (GSM) where carrier spacing is 200 KHz including 8 channels. Carrier signals are modulated with $\pi/4$ - Differential Quadrature Phase Shift Keying (DQPSK), which is one form of Phase Shift Keying –modulation. Typical user data rate when using single time slot is 7.2 kb/s [17].

There are two main operating modes for TETRA mobile terminal. These are Trunked Mode (TMO) and Direct Mode (DMO). When terminal operates in TMO it communicates with TETRA network base station and data (such as a telephone call) to for example to other terminals flows through the network. On the other hand when operating in DMO, mobile terminals are able to communicate directly to each other without network. It is also possible to use mobile terminal in DMO as a relaying station. This way network coverage

can be expanded to another terminal, which is out of network coverage area, but still in the reach of relaying stations DMO. See Figure 12 [17].

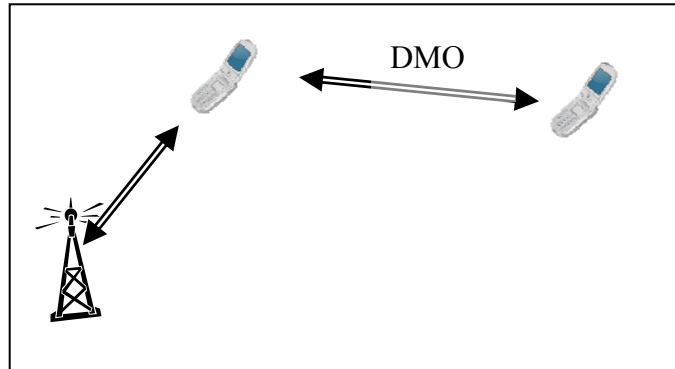


Figure 12. Relaying with DMO

TETRA standard defines six interfaces that are needed for the interoperability. These are shown in Figure 13 and explained below [17].

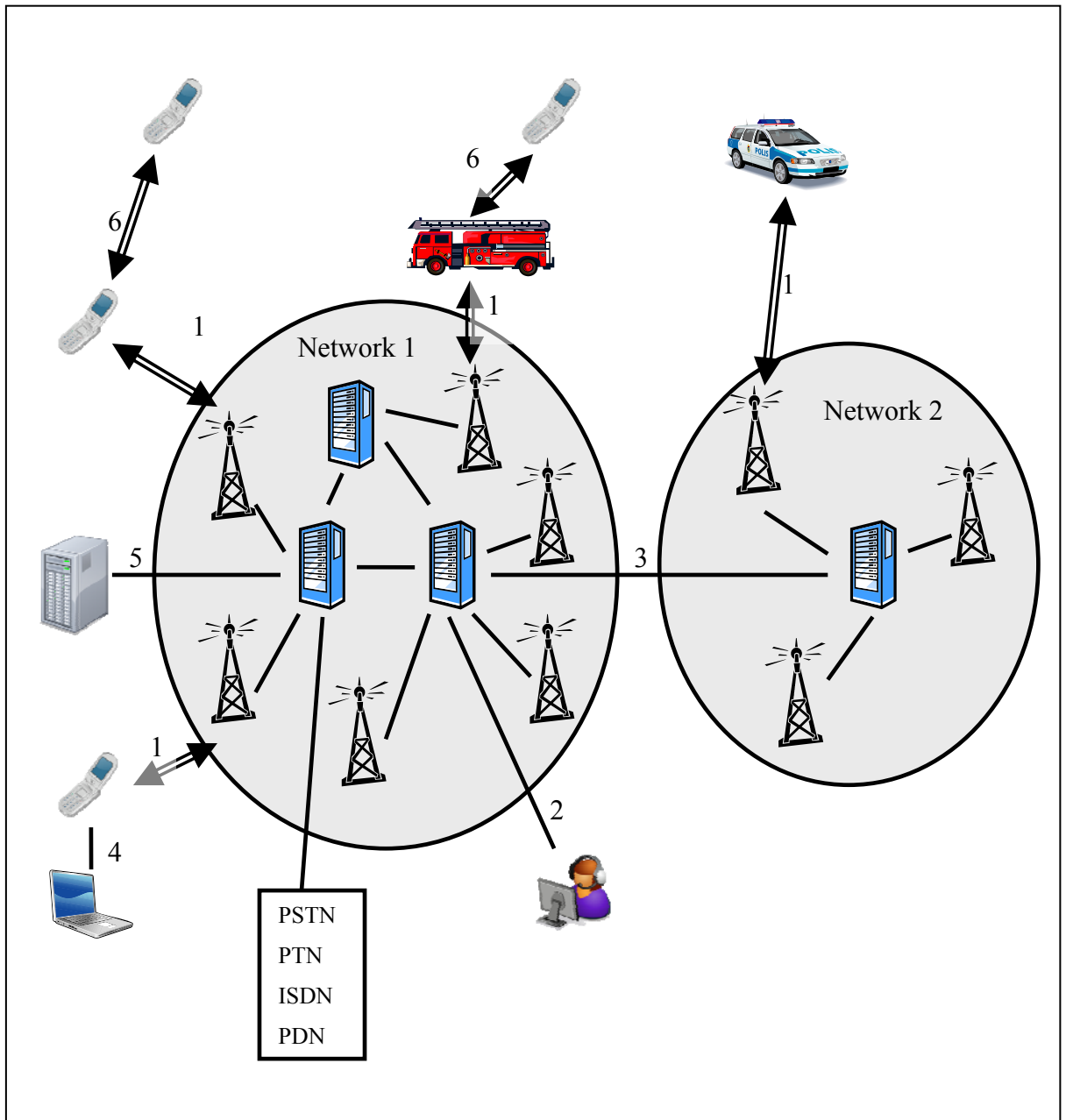


Figure 13. TETRA Network Interfaces

1. TMO interface, between TETRA network and mobile station
2. Line station interface, between TETRA network and line station
3. Inter-system interface, between TETRA networks
4. Terminal equipment interface, between terminal equipment and mobile or line station

5. Network management interface, between TETRA network and network management equipment
6. DMO Interface, between two mobile stations

Additionally there is a possibility to connect a TETRA network to external networks, such as Public Switched Telephone Networks (PSTN), Integrated Services Digital Network (ISDN), Packet Data Networks (PDN) or Private Telephone Networks (PTN). It is important to note that only above mentioned interfaces are standardized; all other parts of TETRA network implementation are open to different implementations. This means that for example the interface between base stations and their controlling stations is vendor specific [17].

4.2 Addressing

TETRA addressing scheme is similar to GSM addressing. There are five different identities and addresses, which are explained in following chapters:

- TETRA Equipment Identity (TEI)
- Mobile Network Identity (MNI)
- TETRA Management Identity (TMI)
- TETRA Subscriber Identity (TSI)
- Network Layer Service Access Point addresses (NSAP)

4.2.1 TETRA Equipment Identity

TEI is a 60-bit code that uniquely identifies a TETRA terminal. Terminal manufacturer allocates the TEI and it can be used by the TETRA network operator. Network operator can for example block a stolen terminal from the network [17]. TEI code consists of Type Approval Code (TAC), Final Assembly Code (FAC), Electronic Serial Number (ESN) and spare bits. Figure 14 shows the structure of TEI-code [18].

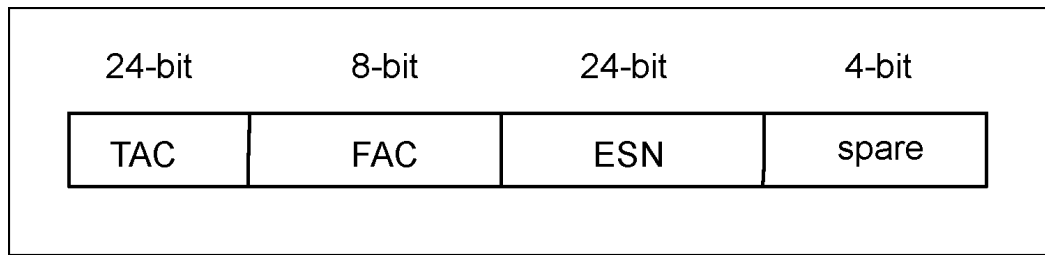


Figure 14. TEI-code

TAC identifies the institute that has performed equipment type approval. TAC codes are allocated by ETSI. Similarly FAC codes are allocated by ETSI and identify the equipment manufacturer and place of final assembly. ESN is a unique serial number within TAC and FAC, and is assigned to every TETRA equipment. Additionally, there are four spare bits in TEI code [18].

4.2.2 Mobile Network Identity

MNI is a 24-bit identity code, which uniquely identifies a TETRA network and is composed of Mobile Country Code (MCC) and Mobile Network Code (MNC). MCC codes have been allocated according to ITU-T Recommendation E.218 [19]. MNC is unique to a TETRA network within a country and is allocated by each country's national administration. MNI-code structure is shown in Figure 15 [18].

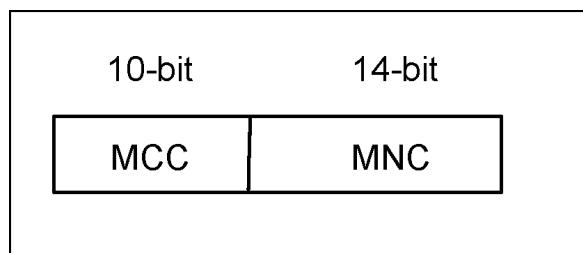


Figure 15. MNI-code

4.2.3 TETRA Management Identity

TMI is a 48-bit identity code for TETRA network management and is allocated by the network operator. It is composed of MCC and MNC concatenated with network specific Short Management Identity (SMI). Structure of TMI is shown in Figure 16 [18].

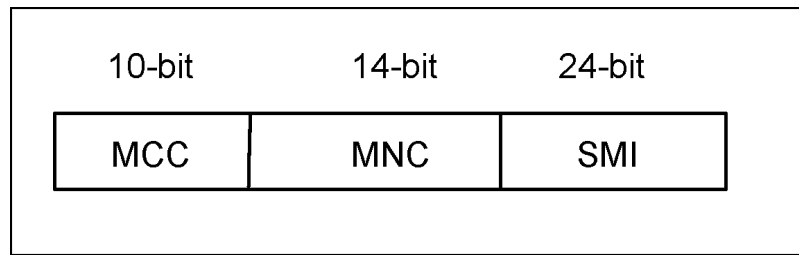


Figure 16. TMI-code

4.2.4 TETRA Subscriber Identity

TSI identifies the TETRA subscriber. It is a 48-bit code consisting of MCC, MNC and Short Subscriber Identity (SSI). Structure of TSI is shown in Figure 17. There are three types of TSI identities: Individual TSI (ITSI), Alias TSI (ATSI) and Group TSI (GTSI). ITSI uniquely identifies a subscriber within a network and ATSI is a temporary alias identifier, which can be assigned to an ITSI. GTSI uniquely identifies a group within a network. However one subscriber may have several GTSI-codes [18].

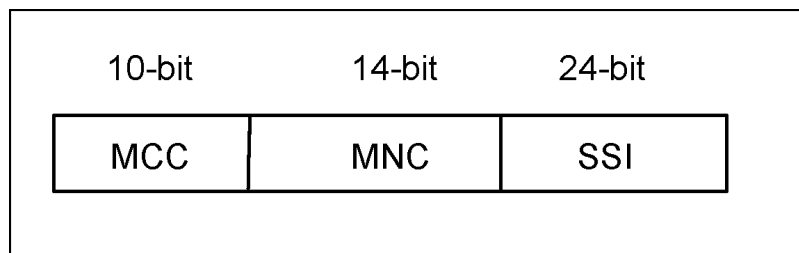


Figure 17. TSI-code

TSI may be truncated within a network and only the 24-bit SSI can be used. Truncated version of ITSI is called Individual SSI (ISSI). Similarly ATSI becomes Alias SSI (ASSI) and GTSI becomes Group SSI (GSSI) [18].

4.2.5 Network Layer Service Access Point Addresses

NSAP addresses are an additional method of addressing for connections outside TETRA network. Outside connection can be for example connections to PSTN, ISDN, PDN or PTN.

4.3 Services

TETRA services can be categorized as bearer services, teleservices and supplementary services. Bearer services are low level services, such that occur on Open Systems Interconnection (OSI) model layers 1-3. On the other hand, teleservices are services that require also higher layers (4-7) of OSI model. This has been illustrated in Figure 18 [17].

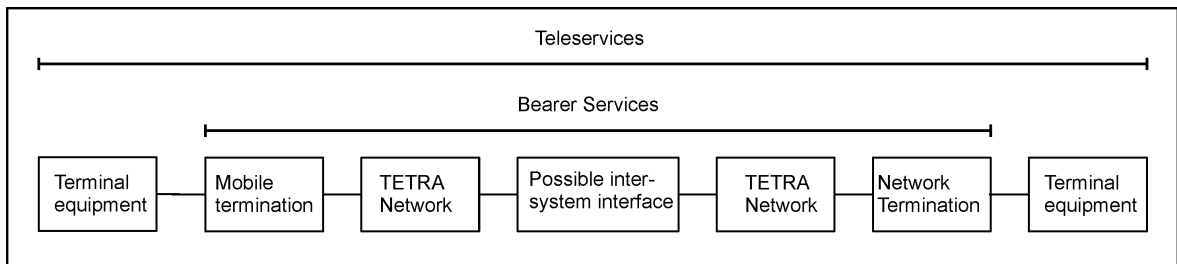


Figure 18. Bearer Services and Teleservices

Bearer services are for example individual calls, group calls or broadcast calls. Teleservices are for example clear or encrypted speech. Supplemental services are services, which either supplement or modify basic services that are part of teleservices or bearer services [17]. Next chapter describes Short Data Service (SDS), which is an important service for this research. Further information on other services can be found in for example reference [17].

4.3.1 Short Data Service (SDS)

SDS is a bearer service for sending messages from one subscriber to one or more subscribers. The messages may be predefined or user-defined. SDS messages are sent using spare capacity of TETRA signaling channel, which is used for communication between the terminal and network. This means that SDS messages may be sent and received during an active call. If an SDS message can not be delivered to the recipient the network may store it for later delivery [17].

There are four types of SDS messages. Where first three are fixed length and the last one is variable sized [17]:

- SDS-1, predefined 16-bit fixed size message
- SDS-2, 32-bit fixed size message
- SDS-3, 64-bit fixed size message
- SDS-4, variable length message with maximum size of 2047 bits

5 EGNOS-Application Using SISNeT

EGNOS application for this research has been implemented using SISNeT (see 3.6). Application is two-parted; SISNeT client is Windows software and the applying of EGNOS augmentations is done with embedded software in TETRA terminal.

Figure 19 shows the measurement system architecture. The Windows software called AGPSDemo fetches SISNeT messages from the SISNeT server through internet. AGPSDemo connects to a TETRA-terminal THR880i (THR880i from here after) through a serial cable. The EGNOS messages from the SISNeT server are then sent to another THR880i with EGNOS modified software (augmented phone from here after). The messages are sent to the augmented phone using SDS-4 messages. The augmented phone receives the SDS-4 messages and parses and stores the EGNOS data. Position information is then calculated in the augmented phone using both the GPS signal and EGNOS data. Position data is collected to a PC using serial cable connected to the augmented phone. Following chapters describe each part of the measurement system in detail.

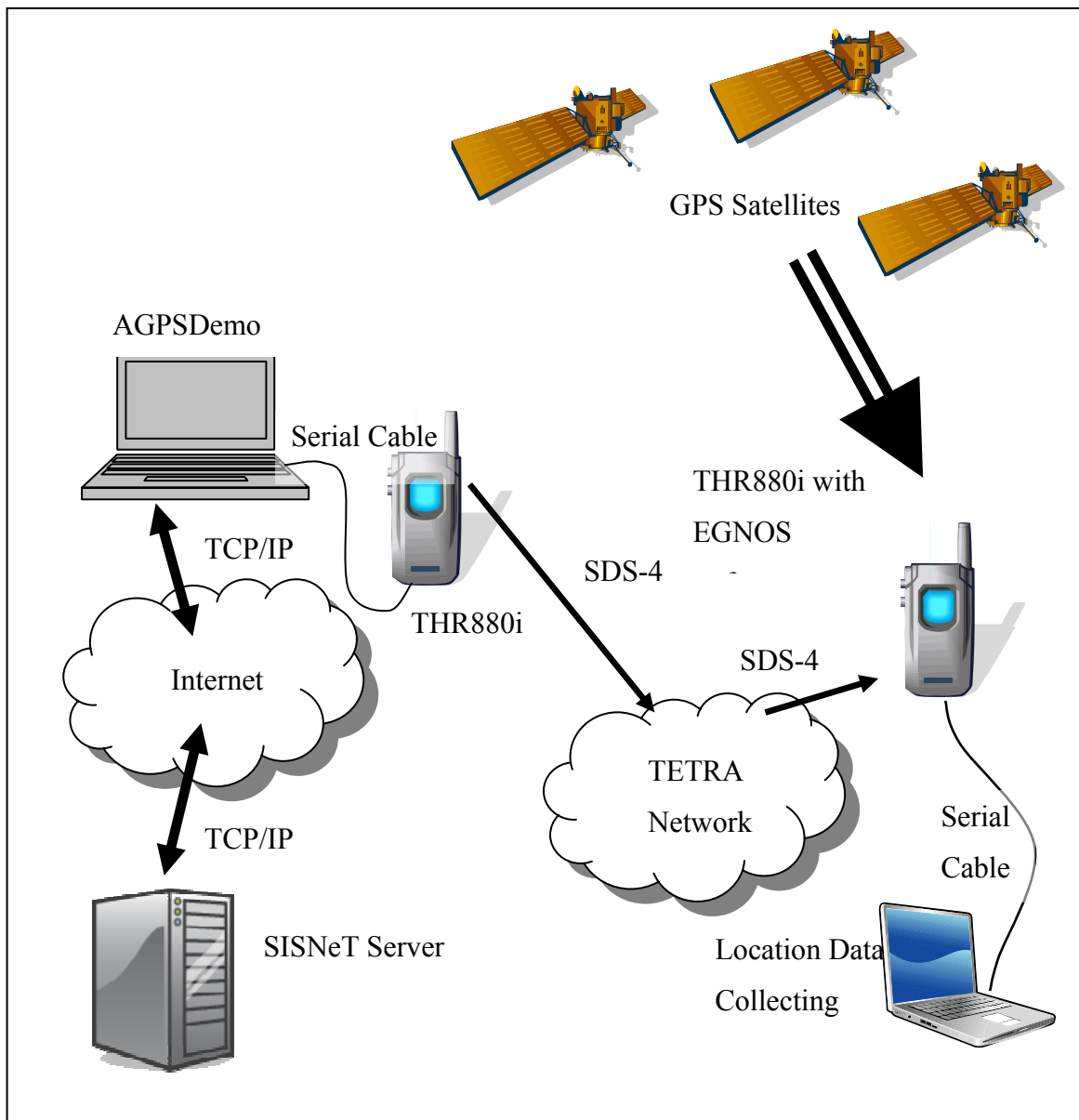


Figure 19. EGNOS Application

5.1 AGPSDemo

Original version of AGPSDemo has been done by Kimmo Haukimäki for his thesis, where he studied Assisted GPS. Assisted GPS is a method to improve the speed of calculating a position after receiver start-up [20]. In this research a new version of AGPSDemo with EGNOS functionality was implemented. This chapter describes the EGNOS functionality of AGPSDemo software. Figure 20 shows the user interface of AGPSDemo.

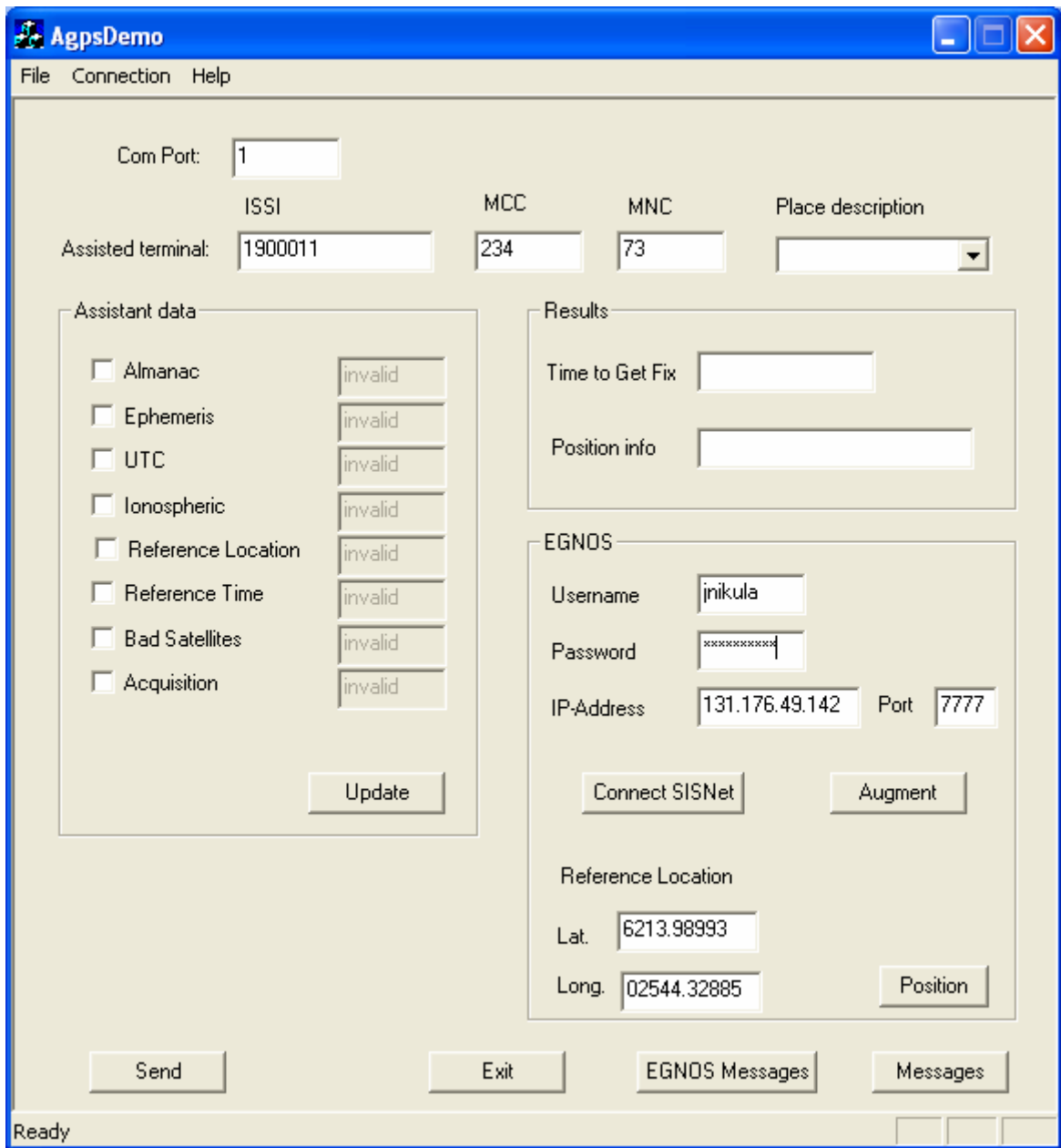


Figure 20. AGPSDemo

When AGPSDemo is started, the user first selects which serial port is used and then connects to the THR880i by selecting Connection->Connect from the menu. Then user can fill in the TETRA-network address for the augmented phone. Furthermore, SISNeT connection details are needed, which includes username, password and the IP-address and port for the SISNeT server. When all the details are filled in, the user may connect to

SISNeT by pressing "Connect SISNeT". Augmenting of augmented phone may be started by pressing "Augment".

There are two message windows, which can be used to monitor the augmenting. Phone messages window is opened by clicking "Messages" and it shows the incoming and outgoing messages of THR880i in hexadecimal format. EGNOS messages window opens from button "EGNOS Messages" and it can be used to monitor the messages coming from the SISNeT server.

Additionally AGPSDemo can be used to ask for position information from the augmented phone. Position info is requested by pressing "Position" button, which causes AGPSDemo to send a position request to the augmented phone every five seconds. AGPSDemo compares the received position information to the reference location filled in the "Reference Location" fields. Received locations are stored in the memory and can be saved to a file. When location info is saved (File->Save As) AGPSDemo saves the received locations, reference location and their differences into a file.

5.2 THR880i

THR880i is a hand portable TETRA radio with an integrated GPS receiver from EADS Secure Networks Oy. GPS receiver horizontal accuracy is 5 meters with 50 % confidence and 10 meters with 95 % confidence. The GPS receiver can provide the user with geographical coordinates or it can be used for remote tracking of the radio. See Figure 21 [22].



Figure 21. THR880i (Copyright EADS Secure Networks Oy)

THR880i also contains a high resolution 65536 colour display with 130x130 pixels. Furthermore the radio enables internet browsing with a web browser and wireless data support. It supports both DMO and TMO operation and operates on frequency bands of 380-400 MHz, 410-430 MHz, 450-470 MHz, 806-825 MHz and 851-870 MHz [22].

5.3 SDS-4 Message

EGNOS messages are sent from AGPSDemo to augmented phone in SDS-4 messages. SDS-4 message structure is defined in reference [21]. EGNOS messages are sent in SDS-4 messages coded as Location system messages, which has been defined with protocol identifier 0x83 in [21]. Within location system there is a subfield called Location system coding scheme. Location system coding scheme identifier 0x80 has been used in this research to identify SDS-4 messages containing EGNOS data. The messages are recognised in the augmented phone by the identifiers mentioned above.

5.4 THR880i with EGNOS Software

Modified software to a THR880i has been developed as part of this research. The software receives SDS-4 messages that have been identified to contain EGNOS messages. These messages are parsed for GPS time, GPS week number and for message type. Message types 0-4, 6, 7 18, 24, 25 and 26 are necessary for improving GPS accuracy and are processed further, rest of the messages are omitted. All data from the mentioned messages is saved to an internal data structure. When GPS positioning is requested, the available EGNOS data in the internal data structure is used to improve positioning accuracy as described in 3.5.

5.5 Position Data Collecting

Measurement environment provides two ways to gather position information. AGPSDemo can be used to send position requests and gather position data remotely from the augmented phone. Alternatively position data can be collected with a serial cable connected to the augmented phone. THR880i can output position data according to National Marine Electronics Association (NMEA) standard 0183. The standard defines a communication protocol for location data over 4800-baud serial cable [23]. The NMEA data can be saved to a file and converted to easily readable format for analysis.

6 EGNOS Accuracy Measurements and Analysis

EGNOS positioning accuracy measurements were performed using the application described in chapter 5. Additionally, a reference device was used to be able to compare EGNOS augmented positioning accuracy to the accuracy of GPS without augmentation. The reference device was a THR880i TETRA radio with standard software. Therefore the only difference between the reference device and augmented phone was the EGNOS modifications. The augmented phone and a reference device were placed in a known location in order to measure the positioning error. Positioning errors were calculated from the measurement data that was collected from both devices.

6.1 Measurement Environment

Augmented phone and the reference device were placed 20 centimeters from each other in such way that both were situated 10 centimeters from the known position. Both devices were on a pole, one meter above ground. The measurement was performed in clear weather in Jyväskylä, Finland in an autumn afternoon. Both devices were given a long time to find all GPS satellites visible before the measurement was started.

The measurement time was half an hour and position data was collected constantly. Both devices were connected to a laptop, which was using serial cables to collect NMEA position data. The collected position coordinates were compared with the coordinates of the known position to calculate the position errors.

6.2 Measurement Results

The differences between known position and measured positions are plotted in Figure 22, Figure 23 and Figure 24. The figures show the error for both the augmented phone and the reference device. Figure 22 shows the error in measured latitude coordinate, Figure 23 shows the longitude coordinate error and Figure 24 shows the error in measured altitude.

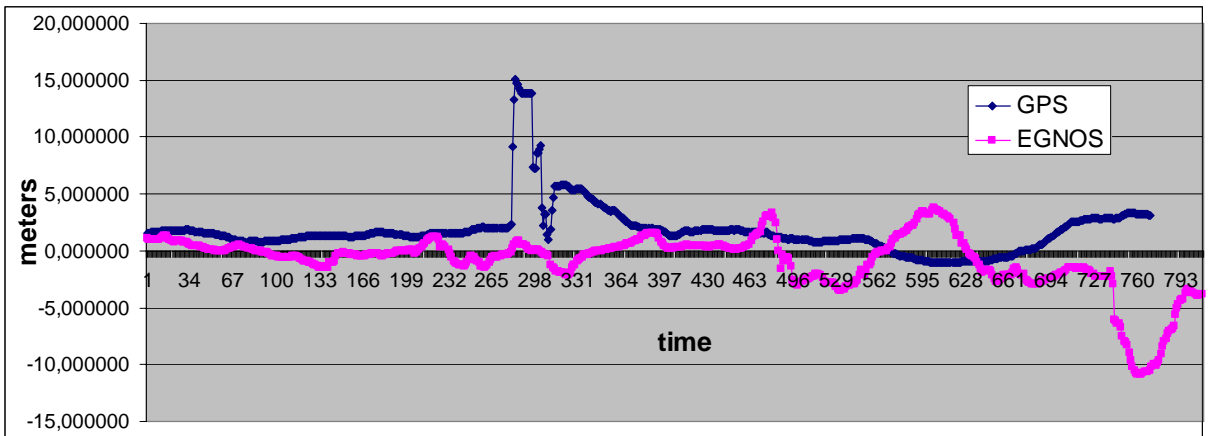


Figure 22. Latitude Error

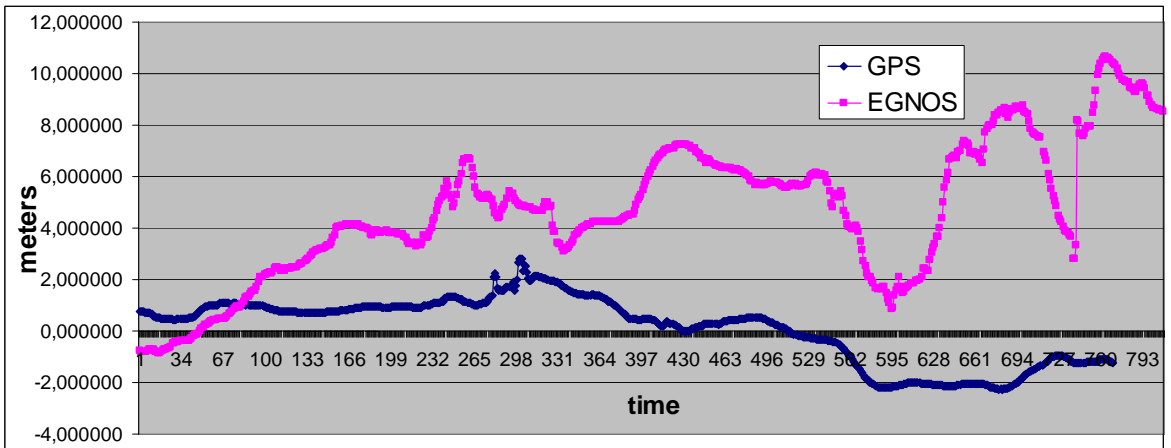


Figure 23. Longitude Error

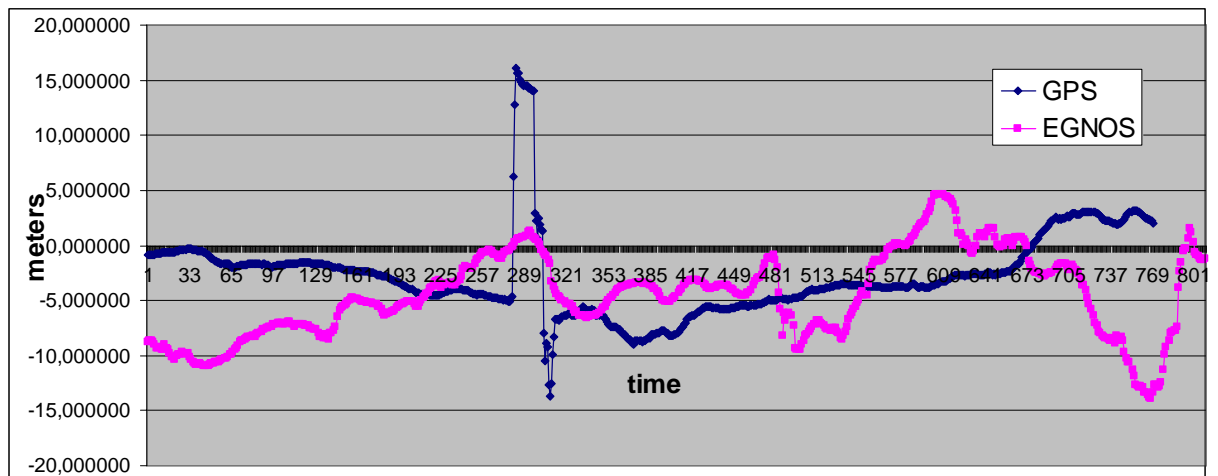


Figure 24. Altitude Error

The augmented phone and the reference device should receive the same GPS signals. However, during the measurements it was found that there are always small differences on signals received. For example a signal from a satellite could be momentarily blocked by an obstacle, while the other device is still receiving the blocked signal. These differences on the received signals can be assessed by comparing receiver's PDOP value (see 2.7) and the number of satellites used during the measurement. These values were obtained from the NMEA data received from the augmented phone and the reference device. Figure 25 shows the PDOP and Figure 26 shows how many satellites were used for calculating the receiver position. Both figures show the values on the same time scale as the previous figures presented the latitude, longitude and altitude errors. The data presented in these figures is analysed in the following chapters.

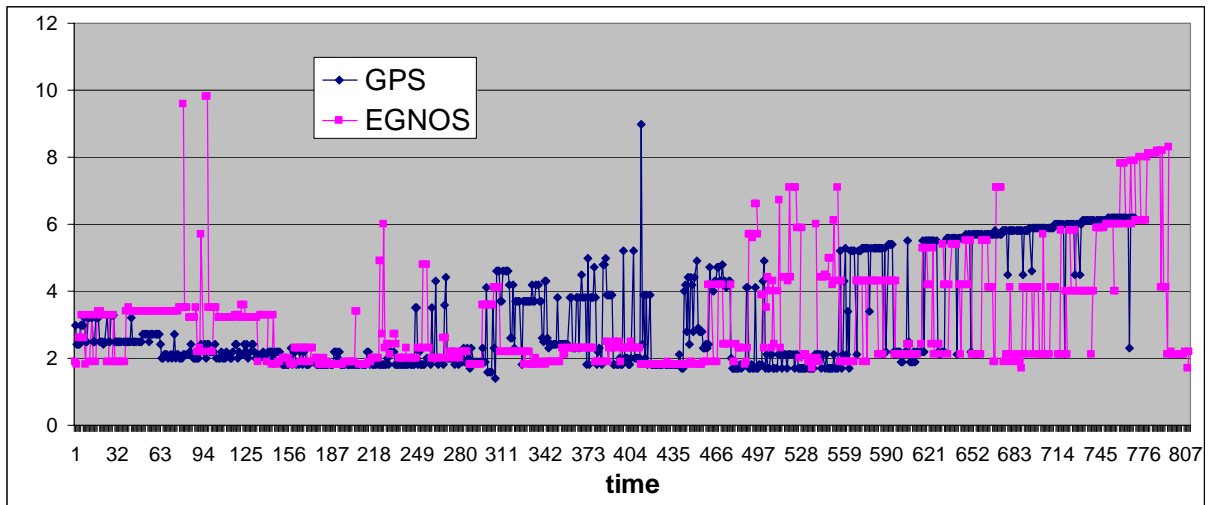


Figure 25. PDOP

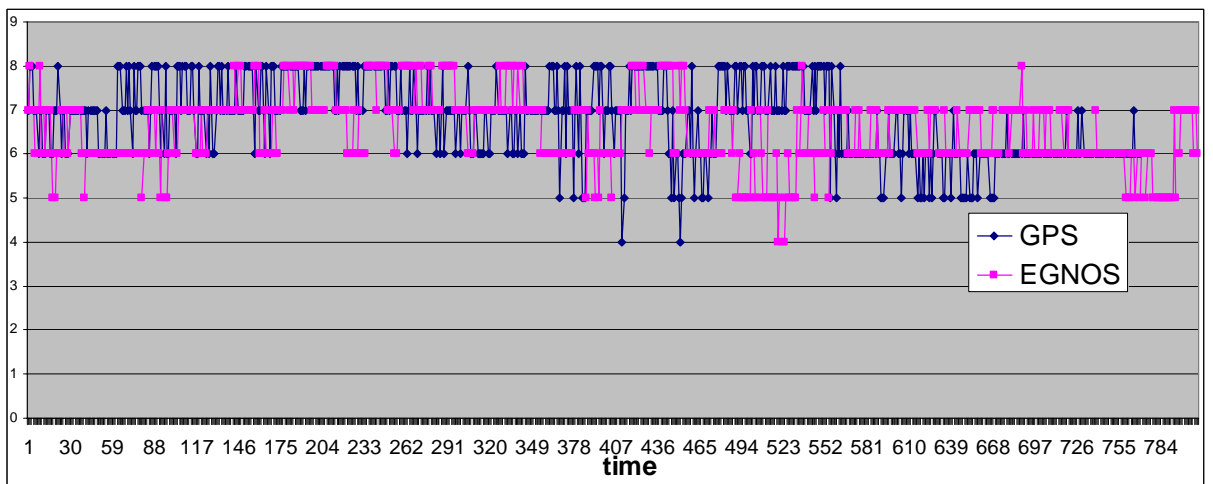


Figure 26. Number of Satellites Used for Positioning

6.3 Analysis

It is obvious that the results are not what was expected. The intended horizontal accuracy for EGNOS augmented positioning is about 1-2 meters and the intended vertical accuracy is 2-3 meters [9]. It can be seen in the figures in previous chapter that the accuracy has not been significantly improved and the longitude coordinate accuracy even seems to have decreased. Furthermore, the horizontal accuracy of EGNOS augmented positioning does

not reach 1-2 meters, but is closer to 10 meters. Similarly the vertical accuracy does not reach 2-3 meters, but is closer to 15 meters.

Figure 26 shows that both receivers have been using at least four satellites during the entire measurement. Typically both receivers have used 6 to 8 satellites to calculate the position. Approximately between points 470 and 550 it can be seen that the augmented phone has been using less satellites than the reference device. Otherwise, there are no significant differences in the number of satellites used. Similarly in Figure 25 between points 470 and 550 the augmented phone's PDOP reaches somewhat higher values than the PDOP of the reference device. This means that the augmented phone has been unable to use some of the satellites available, which has also momentarily increased the PDOP value. However, during rest of the measurement time satellite geometry used by the receiver's has been reasonably uniform. It is likely that the increased PDOP value between points 470 and 550 has momentarily decreased the positioning accuracy of the augmented phone. Nevertheless, it can be concluded that most of the time both receivers have received similar GPS signal and any significant differences in the position accuracy are caused by the EGNOS corrections.

6.3.1 Related Research

Finnish Geodetic Institute in co-operation with ESA has performed a similar research, where a handheld SISNeT receiver was developed. The receiver consisted of a Pocket PC and a GPS receiver. Another research was performed in Aalborg University, where a group of students developed software for GPS receiver with EGNOS capability [24][25].

The research by Finnish Geodetic Institute was performed using the EGNOS corrections provided by SISNeT. SISNeT corrections were obtained from the internet with a wireless General Packet Radio Services (GPRS) connection. Reference measurements were also performed with a fixed internet connection. The GPS receiver was a commercial receiver card that was inserted into the Pocket PC. The GPRS connection was obtained with a GPRS modem card.

There was no access to the GPS calculations or to the pseudoranges, because the GPS receiver was commercial. However, it was possible to obtain GPS coordinates from NMEA messages that the receiver provided. The EGNOS pseudorange corrections from SISNeT were used to estimate coordinate corrections for GPS. This was possible by using GPS ephemeris data that was received from SISNeT. Another issue was that the GPS coordinates already contained GPS single frequency ionosphere model corrections. The effect of GPS ionosphere correction to the GPS coordinates had to be removed, in order to be able to use the ionosphere corrections that are part of the EGNOS pseudorange corrections. In order to remove the effect of GPS ionosphere correction, the GPS ionosphere model data was needed. Hence, SISNeT also provides GPS ionosphere model data [24]. The approach in Geodetic Institute's research is slightly different to this research. As explained in chapter 5.4, in this research the corrections were applied directly to the GPS pseudorange data rather than applying them to the coordinates that the GPS provides. It should be noted that the approach used in Geodetic Institute's research may deteriorate the results slightly, because it is not the way the corrections should be applied according to reference [11].

Geodetic Institute performed two measurements; one with GPRS data connection and second with fixed internet connection. When GPRS was used, only 72% of all EGNOS messages were received. With fixed internet connection all messages were received. When using fixed connection the position accuracy was significantly improved and EGNOS intended positioning accuracy of 1-2 meters in latitude and longitude was achieved. Similarly the altitude accuracy was within EGNOS limits of 2-3 meters. The GPRS connection resulted in slightly poorer results. However, the difference between fixed and GPRS connections was mostly less than 0.5 meters [24].

As mentioned earlier, another similar research was performed in Aalborg University, Denmark. The research used EGNOS corrections that were received directly from the GEO satellites. Also the software for a GPS receiver was developed as part of the research. The corrections were applied directly to the GPS pseudoranges according to reference [11]. The research reports that the EGNOS long term corrections were found to decrease the positioning accuracy. However, it is noted in the research that this may have been caused

by a software error. Even without the EGNOS long term corrections the position accuracy was found to improve significantly and the EGNOS accuracy was mostly achieved [25].

The approach in Aalborg University's research is very similar to this research, in both researches the implementation has been done according to reference [11]. The only difference between this research and the research done in Aalborg University is the way EGNOS corrections were obtained. This research used SISNeT and the research performed in Aalborg used the GEO signal directly [25].

Based on these similar researches that have been performed it can be said that the measurement system used in this research must be faulty. In similar researches the intended EGNOS accuracy has been achieved, but in this research the accuracy has not been improved. There are several possible causes of failure. These causes are evaluated in the following chapters.

6.3.2 Outdated Augmentation Data

During this research the SISNeT server provided by ESA was not functioning satisfactorily. The server was providing augmentation data only approximately 60 percent of time. Furthermore the data provided by the server was partly outdated. Typically the server was providing 180 seconds old data and occasionally even older data. This means that short term corrections were useless and most of the long term corrections were also useless.

As mentioned in chapter 3.4.5, fast correction message time-out period is determined from the degradation factor indicator. During the measurements the degradation factor was constantly such that the time-out period for fast corrections was 18 seconds. Obviously if as mentioned above the messages received are 180 seconds old the fast corrections cannot be used. On the other hand, in chapter 3.4.12 it is pointed that long term corrections time-out period is 360 seconds. In practice this meant that most of the time the long term corrections could neither be used.

Only the ionosphere corrections provided by the SISNeT server were usable, but they also suffered from the outdated messages and their time-out period (600 seconds) was some times reached. It should also be noted that the problem is not only the time-out period, but contents of the messages were also old. The ionospheric delays calculated by the augmented phone were based on the ionosphere's situation at least 180 seconds ago. Although typically the changes in the ionosphere are slow varying [7].

6.3.3 Incorrect Augmentation Data

As explained in the previous chapter, the SISNeT server was found to be very unreliable. This raises suspicion also on the accuracy of the corrections it is providing. Unfortunately there was no way to ensure that the SISNeT server was providing valid data. If the corrections provided were not valid this would of course explain the poor results obtained in this research.

6.3.4 Software Error

The software used in the augmented phone has been carefully inspected and reviewed for errors. Nevertheless, given the results, it is likely that there is an error or errors in the software. If there are errors in the software, they may have at least partly caused the poor positioning accuracy of the augmented phone during the measurements.

6.3.5 Ionospheric Grid Point Coverage

EGNOS augmentation data is provided to be used in Europe. This means that ionospheric delay is measured above Europe. The measurements were performed in Finland, which is on the edge of EGNOS coverage area. It was noted during testing of augmented phone's software that if a satellite in receiver's visibility is too far east the ionosphere pierce point is out of EGNOS coverage area. In these cases the EGNOS ionosphere corrections cannot be used and GPS ionospheric delay model was used instead. This problem has probably had a small effect on the augmented phone's positioning accuracy.

6.3.6 EGNOS Malfunctions

As mentioned in chapter 3.1 EGNOS system is currently under testing and cannot be used for safety-of-life purposes. This means that EGNOS reliability is not guaranteed. Therefore it is possible that the poor measurement results could have been caused by an EGNOS malfunction. However, EGNOS is already widely used and therefore a malfunction can be considered to be very unlikely.

7 Conclusions

This thesis studies EGNOS augmented GPS positioning. The goal of the research has been to determine EGNOS accuracy when using a TETRA radio with GPS receiver. EGNOS augmentation messages were obtained from the internet using SISNeT service provided by ESA. SISNeT messages were first received with PC client software and then forwarded to the TETRA radio using SDS-4 messages. SDS-4 messages are received by the TETRA radio and the EGNOS messages inside SDS-4 messages are decoded. The decoded data is combined with the GPS measured data in order to improve positioning accuracy.

The measurements failed to prove that EGNOS can be used to improve TETRA radio's positioning accuracy. There are several possible causes for the unexpected measurement results. These are software error, outdated augmentation data, incorrect augmentation data, lack of EGNOS coverage or malfunction in EGNOS system. It is likely that the inaccurate positioning is a result of some or all of the causes mentioned. The augmentation data was partly outdated as it was found to be approximately three minutes old, which without a doubt has affected the accuracy. However, even with outdated data there should have been some improvement in the accuracy; therefore it is likely that there is a software error in the measurement system. The measurement system was thoroughly reviewed, but the inaccuracy could not be solved. There was no means to verify the correctness of the augmentation data received. This means that incorrect augmentation data or EGNOS malfunction may also have caused the results.

There are several ways to further study the subject; The SISNeT server has been causing many problems during the research. The server could be replaced by a commercial EGNOS receiver, which would receive augmentation data directly from the GEO satellites. The augmentation data could either be broadcast using a server which mimics the ESA SISNeT server or it could be sent directly in SDS-4 messages to the augmented phone.

Another approach to improve the results could be to use ESA's EGNOS Data Access System (EDAS), which is a commercial service that is to be released in near future. Similarly to SISNeT EDAS will provide EGNOS augmentation data through internet, but with guaranteed performance. Furthermore, EDAS will provide more flexible client

interface [26]. However, it should be noted that SISNeT service availability was found to be poor, which may mean that similar problems may arise with EDAS as well.

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