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Softwarové rádio a jeho aplikace v GNSS

Software Radio and its Application in GNSS

Summary

Software radio or software defined radio (SDR) is a modern concept of the design of the radio systems where the crucial part of the signal processing is realized by software in programmable devices.

In this paper we propose an Experimental GNSS Receiver and its application. The experimental GNSS receiver is a real-time software receiver designed at the CTU for investigation of GNSS and especially Galileo signal processing.

The experimental GNSS receiver was used for investigation of the EGNOS system availability for a land mobile user. The EGNOS is so far the sole GNSS system, which provides safety of life service in the European region. The main problem of EGNOS for mobile users is shadowing of the EGNOS satellite by various obstacles.

The EGNOS mobile channel based on the Markov process was developed on the theoretical part of this research. The experimental part covers model parameters determination for various environments in the Czech Republic, channel model verification, and mobile experiments with optimal EGNOS receiver for land mobile users.

For the purpose of proposed research, the special signal processing based on parallel correlation was implemented into the experimental GNSS receiver. Proposed signal processing calculates the cross-correlation function of the received signal and replica simultaneously for all considered delays and thereby accelerates the acquisition of the EGNOS spread spectrum signal.

Research has shown that EGNOS service is not generally available in the environment of the Czech Republic for land mobile users. The safety of life navigation service should be ensured by another method, for example by distribution of the EGNOS data via an alternative channel.

Souhrn

Pojem softwarové rádio nebo softwarově definované rádio (SDR) se v asi pěti posledních létech užívá pro moderní koncept konstrukce rádiových systémů, ve kterých je rozhodující část zpracování signálu realizována softwarově v programovatelných obvodech.

V přednášce je předložena koncepce experimentálního GNSS přijímače a jeho aplikace. Experimentální GNSS přijímač je softwarový přijímač signálů družicových navigačních systémů GPS, GLONASS a GALILEO pracující v reálném čase, který byl zkonstruován na katedře radioelektroniky Fakulty elektrotechnické ČVUT pro účely výzkumu metod zpracování signálů GNSS, především pak signálů systému Galileo.

Přijímač byl použit při výzkumu dostupnosti systému EGNOS pro pozemního mobilního uživatele. Systém EGNOS je doposud jediný GNSS systém, který poskytuje v evropském regionu navigační službu s garancí bezpečnosti (safety of life). Hlavní problém při použití systému EGNOS mobilním uživatelem je nízká elevace družic a z toho plynoucí jejich zakrývání různými překážkami, budovami ap.

V *teoretické části výzkumu* byl navržen model mobilního kanálu EGNOS používající aparátu Markovových procesů. *Experimentální část výzkumu* zahrnovala určení parametrů tohoto modelu pro různá prostředí v České republice, ověření jeho správnosti a pokusy s mobilním příjmem pomocí optimálního přijímače EGNOS pro pozemního mobilního uživatele.

Pro účely výzkumu byla navržena a implementována do experimentálního přijímače zvláštní metoda zpracování signálu založená na paralelní korelaci. Počítá vzájemnou korelační funkci přijímaného signálu a repliky současně pro všechna potřebná zpoždění a tím urychluje vyhledávání signálu EGNOS.

Při experimentech se potvrdilo, že služba EGNOS není pro mobilního uživatele v České republice všeobecně dostupná. Bezpečnou navigační službu je tedy třeba zajistit jinými metodami, například distribucí dat EGNOS pomocí jiného komunikačního kanálu.

Klíčová slova: družicová navigace, zpracování signálu, softwarové rádio, softwarově definované rádio, SDR, GPS, GLONASS, Galileo.

Keywords: Satellite navigation, signal processing, software radio, software defined radio, SDR, GPS, GLONASS, Galileo.

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Content

1. Introduction

Software radio or software defined radio (SDR) is modern architecture of radio communication systems whose function is defined by software. SDR performs a significant part of signal processing in a computer or a reconfigurable (programmable) logic device. The aim of this design is to develop a radio that can receive and transmit new forms of radio protocol and modulation just by running new software.

Software radios have many applications in military communication, cell phones and Global Navigation Satellite Systems (GNSS), where the modulation schemes, coding and protocol are frequently changed. One of the first software radios was a U.S. military project named SpeakEasy. The primary goal of the SpeakEasy project was to use programmable processing to emulate more than 10 existing military radios, operating in frequency bands between 2 and 200 MHz.

The first post processing Global Positioning System (GPS) software implementation was described by Denis Akos in 1997 [2].

The concept of the Experimental GNSS Receiver – real-time GNSS software receiver – designed for research and development purposes was proposed at the Czech Technical University in 2000. Its aim has been to study the processing of GPS and Galileo signals. We have implemented into it not only processing of GPS signals but also GLONASS and EGNOS signals and prepared it for GALILEO, too.

The Experimental GNSS Receiver was used for investigation of the EGNOS service availability for land mobile users. The proposed method utilizes specialized signal processing software for EGNOS channel model parameter determination, model validation and for design of the optimal EGNOS receiver for land mobile users.

2. GNSS systems

2.1. Principle of operation

The Global Navigation Satellite Systems (GNSS) utilize the ranging navigation method. The GNSS receiver calculates its position from measured distances between itself and three or more GNSS satellites [4]. The measured time delay between the transmission and reception of each GNSS radio signal gives the distance to each satellite, since the signal travels with a known speed. The signal can also carry information about the satellite location, so computation of user receiver position is possible.

The GNSS signal is optimized for range measurement. Its spectrum is spread by the modulation by the pseudo-random ranging code $C(t)$, which ensures good correlation property of the signal. Prime GNSS systems such as GPS and GLONASS use BPSK(*m*) modulation schemes (1)

$$s_{BPSK}(t) = C(t)D(t)\cos(\omega_c t), \quad (1)$$

where signal $D(t)$ represents navigation data and ω_c is the angular frequency of the carrier wave. A value of *m* expresses the bit rate of *C*(*t*); it is equal to $m.f_0$, where f_0 = 1.023 MHz.

Some GNSS signals, usually called pilot signals, are modulated by the ranging code *C*(*t*) only.

Modernized GNSS signals and new GNSS systems such as Galileo employ more complex modulation like the Binary Offset Carrier BOC(*m*, *n*) scheme with better correlation property.

The BOC modulated navigation signal can be expressed as

$$s_{BOC}(t) = C(t)D(t)sc(t)\cos(\omega_c t), \quad (2)$$

where signal $sc(t)$ denotes the square wave subcarrier. The additional square wave modulation causes a split of the main spectral lobe into two symmetrical components, which are shifted from the centre frequency of the signal bandwidth. The parameter *m* stands for the ratio between subcarrier frequency and the reference frequency f_0 = 1.023 MHz, and *n* stands for the ratio between the code $C(t)$ rate and f_0.

The standard processing of the GNSS ranging signals uses the correlation reception method [4]. The received signal is converted down to the baseband and despread by multiplication by the replica (known part of the signal) and filtering (averaging or coherent integration).

Today's GNSS systems GPS and GLONASS were developed as military systems and do not meet the civilian requirements on position integrity and safety. The civilian requirements on the GNSS systems are solved by

- Augmentation of the existing systems
- Modernization of the GNSS systems
- Construction of the new civilian GNSS systems

2.2. EGNOS

The EGNOS (European Geostationary Navigation Overlay Service) [5] is a European satellite-based augmentation system of GPS and GLONASS, which provides users with wide-area differential corrections and integrity information.

The EGNOS enhances performance of the GNSS systems enabling service with guaranteed position accuracy, integrity and safety. This service is called safety of life service and is required, for example, in civilian aviation navigation, ship navigation and many other applications.

The EGNOS system is controlled by its ground segment, which monitors the GPS and GLONASS satellites above continental Europe and calculates differential corrections for improvement of position precision and generates integrity information. The generated data are distributed to the user via geostationary satellites. The signals of these EGNOS satellites are similar to GPS ranging signals and can be used for distance measurements. EGNOS satellites therefore increase the number of satellites in the navigation system constellation. The EGNOS signal utilizes BPSK(1) modulation. The EGNOS navigation data are organized into one-second messages, which carry different types of data.

The EGNOS standard defines the maximum age of partial items of EGNOS data for safety of life navigation. The EGNOS receiver, therefore, must ensure a sufficient update rate of these data.

The problem of application of the EGNOS for a land mobile user is limited by the availability of the EGNOS signals disseminated via geostationary satellites due to their shadowing by obstacles.

3. GNSS Software Receiver

3.1. Receiver concept

In the past, software GNSS receivers were used mainly for research and education purposes and for receiver prototyping [2], but this concept has begun to be used in mass receiver production, too. The aim of this paragraph is to discuss three concepts of the software receiver utilized in GNSS.

The **post processing GNSS software receiver** [6] does not work in real time. The processed signal first has to be stored in a computer or generated artificially by the GNSS signal simulator. The GNSS receiver usually runs on a PC workstation; receiver algorithms are programmed in C++ or Matlab.

The **conventional real-time GNSS SDR receiver** (Fig. 1) replicates the architecture of the conventional GNSS receiver. Signal processing is divided between correlators, which are programmed to the FPGA, and a processor.

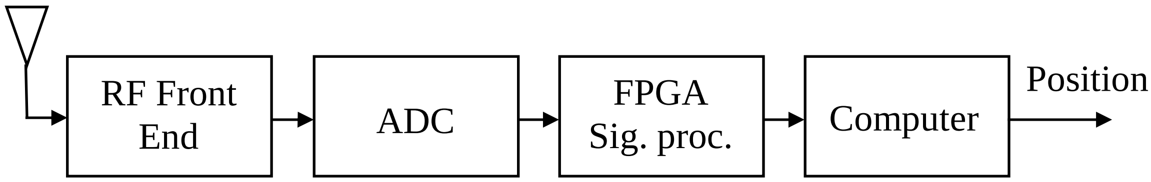

Fig. 1. Convention GNSS SDR receiver architecture

The strength of this receiver concept is in its high flexibility while keeping high performance.

The **processor-only SDR receiver solution** (Fig. 2) performs all signal processing, including correlation reception tasks, in the DSP, universal or embedded processor. The receiver processor, therefore, must have adequate computation power.

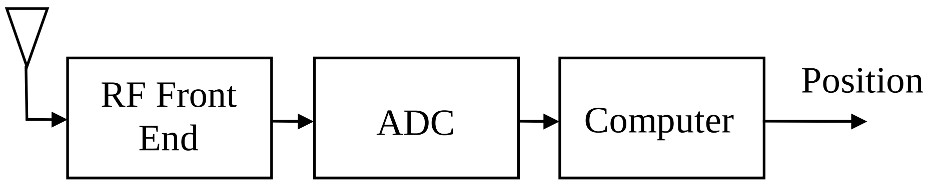

Fig. 2. Processor-only GNSS SDR receiver architecture

Processor-only software GPS receivers have wide possibilities of implementation in mobile phones, digital cameras and similar devices equipped with high-performance embedded processors because of low integration cost [15], [16].

3.2. Experimental GNSS Receiver

The Experimental GNSS Receiver [10], [12] is an SDR receiver developed at the Czech Technical University for research and receiver development purposes. The main objectives in the receiver development have been to have a development tool with the capability to process all available GNSS signals including signals of future Galileo and to ensure enough computational power for the implementation of advanced signal processing methods.

The first receiver hardware was available in 2002. The latest receiver hardware (Fig. 3) supports simultaneous processing of the GNSS signals at up to four navigation frequencies in four parallel channels. The bandwidth of each channel is 24 MHz. The computational power of the FPGA used with an embedded computer based on a PowerPC processor core is sufficient for full rate processing of up to four navigation frequencies and an adequate number of navigation signals. The problem arises only with the coherent processing of the Galileo E5 signal because of the 70 MHz bandwidth.

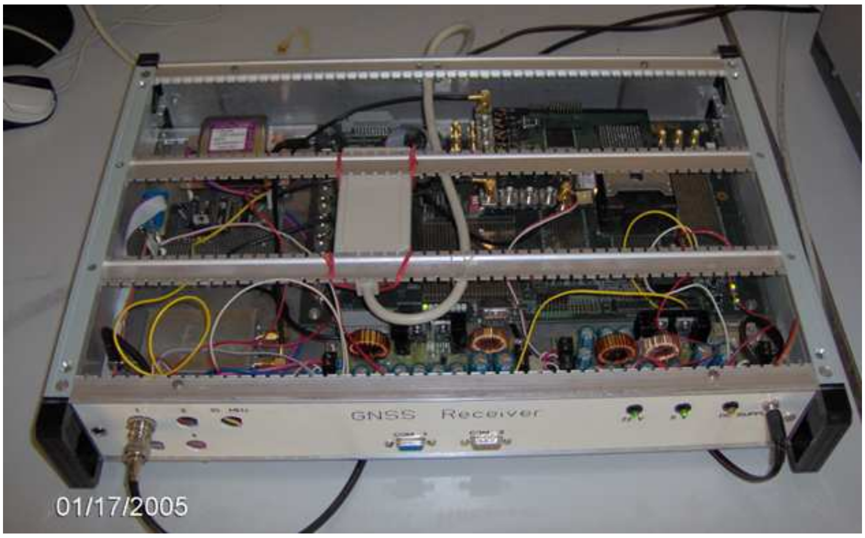

Fig. 3. Experimental GNSS receiver

The concept of an advanced software receiver with higher performance and capability to process the Galileo E5 signal was also prepared; the receiver is in the process of functional sample manufacturing.

4. Availability of the EGNOS service for land mobile users

The important application of the Experimental GNSS Receiver is its use for experimental measurements for investigation of the availability of EGNOS safety of life service for land mobile users [8], [9].

4.1. EGNOS channel model

The topic of this chapter is the construction of a model of a mobile EGNOS channel. The shadowing of the line of sight (LOS) of the signal is commonly modeled by the two-state Markov random process [7].

For the purpose of this project, the EGNOS mobile channel will be modeled as the Markov random process with states 0 – blocked and 1 – unblocked LOS. The partial transition intensity matrix of the process is given by

$$\mathbf{A} = \begin{pmatrix} \alpha_{00} & \alpha_{01} \\ \alpha_{10} & \alpha_{11} \end{pmatrix} = \begin{pmatrix} -\lambda & \lambda \\ \mu & -\mu \end{pmatrix}, \qquad (3)$$

where λ is the partial intensity of the unblocked LOS and μ is the partial intensity of the blocked LOS. Probabilities π_0 and π_1 of blocked and unblocked states are given

$$\pi_0 = \frac{\lambda}{\lambda + \mu}$$
$$\pi_1 = \frac{\mu}{\lambda + \mu} \quad (4)$$

Due to the physical nature of the shadowing process the time variable T of the Markov process was assigned to the physical distance traveled. It guarantees model invariability to the speed of the user movement.

The implemented EGNOS channel coding (convolutional code with constrain length 7 without interleaving) has pure burst error correction capability. The impact of the channel coding to the mobile EGNOS message reception therefore can be neglected. The probability of correct reception of the message is then given

$$r_m = \pi_1 e^{-\mu T_Z v} \quad (5)$$

where T_Z denotes the message length and v is the speed of the user movement.

The proposed channel model was then used for the derivation of more complex statistics of the EGNOS message reception like the probability of reception of at least one message from N messages, etc. [8].

Antenna Diversity Reception

The possible improvement of the EGNOS signal availability to land mobile users by use of the antenna diversity reception technique was analyzed as well. Theoretical analysis was done under the assumption that the message is properly received using antenna diversity technique when at least one antenna is in an unblocked state for the duration of the message. The probability of EGNOS message reception for two antennas placed in the axis of user movement at distance d is, under the mentioned assumption, equal to sojourn $r_{2a}(T)$ of the antennas in operational states (at least one antenna is unblocked for that time) for message duration T_Z

$$r_{2a}(T) = r_{01}(T)s_{01} + r_{10}(T)s_{10} + r_{11}(T)s_{11}, \quad (6)$$

where $r_{XY}(T)$ denotes the conditional probability of sojourn in any functional state for time T under the condition of initial state XY and s_{XY} is the probability of initial state XY.

4.2. Land mobile experiment

The aim of the EGNOS land mobile channel measurement is determination of the theoretical model parameters for various environments and model validation. In the frame of this task, two types of measurement were carried out:

- Mobile measurement of the EGNOS satellite shadowing
- Mobile reception of the EGNOS messages

Experimental equipment capable of a quick response to the EGNOS satellite signal was needed for proper EGNOS channel measurement. Common navigation receivers are not applicable due to the "long" response on the signal, typically about 1s. It would distort the result or slow down the measurement enormously. These reasons led to the development of special equipment based on the Experimental GNSS Receiver [9]. The signal processing is based on a parallel algorithm capable of responding very quickly to the signal. This algorithm was used for both EGNOS signal detection and for fast acquisition in mobile EGNOS message reception experiment.

4.3. Fast detection unit of the EGNOS signal

The speed-up of the navigation signal acquisition can be based on the massive correlation principle that is used, for example, by acquisition units of high sensitive or indoor navigation receivers. The main idea of the proposed method is the calculation of the cross-correlation function between the received signal and the replica simultaneously for many delay and frequency bins.

The low value of the Doppler shift of the EGNOS GEO satellite signal enables considerable reduction of the search space in comparison with the GPS satellite, where the Doppler shift is much higher due to the satellite movement. With respect to the frequency error of the Experimental GNSS Receiver frequency the standard and maximum considered speed of user movement during experiments 20 m/s, the frequency uncertainty is a maximum of ±250 Hz.

The block diagram of the proposed algorithm for signal detection is shown in Fig. 4. The signal is coherently integrated for 1 ms, the frequency bin is therefore a minimum of 500Hz, so the frequency search can be omitted completely. The implemented algorithm calculates the cross-correlation function between the received signal and the replica in parallel for all delay bins in real time. The response of the algorithm to the EGNOS signal is therefore determined by the non-coherent integration time, which is 8 ms.

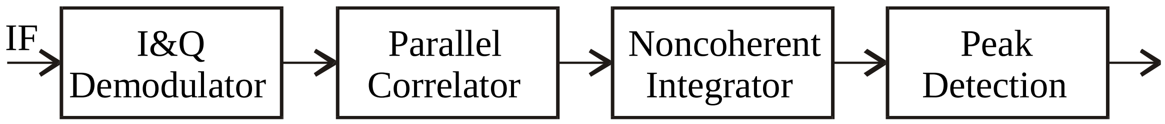

Fig. 4. EGNOS signal detection algorithm

4.3. EGNOS receiver for land mobile users

The EGNOS receiver for mobile EGNOS message reception was developed and implemented in the Experimental GNSS Receiver platform. The proposed receiver is specially optimized for mobile satellite channels. The signal processing is split into the real-time part and the offline part. Real-time processing is programmed in the receiver FPGA with embedded computer and covers:

- Signal acquisition
- Code tracking
- Data acquisition

The signal acquisition is speeded up by the fast detection unit described in the previous paragraph. The 1 ms samples of the correlation peak are stored in the computer for further offline processing, which covers:

- Carrier recovery
- Bit synchronization
- Message synchronization
- Soft Viterbi decoding of the convolutional code
- CRC check
- Message decoding

The carrier recovery uses non-causal, two-step algorithms; the first step implements coarse carrier recovery and second implements fine recovery. The algorithm is featured with minimal synchronization time and considerable robustness. The remaining implemented algorithms are the standard ones used in common navigation receivers.

4.4. Experimental Results

The mobile experiments were realized in two sessions. The first session was carried out at the beginning of 2005. The aim of this session was an investigation of the shadowing process of the EGNOS satellites based on the distance traveled in different environments. The EGNOS system Test Bed

(ESTB) with operational satellites IOR on elevation 15° and partially AOR-E on elevation 26° was available at that time.

The second session was realized at the beginning of 2006. The regular EGNOS satellites ESA Artemis with elevation 32° and Inmarsat III F5 with elevation 32° were studied. The aim of the second session was investigation of the EGNOS message reception availability.

EGNOS signal availability

Typical examples of the shadowing process with respect to the distance traveled for country and city environments are displayed in Fig. 5. On the basis of realized mobile experiments, the typical values of μ and λ (3) were determined for the Markov model of the EGNOS satellite shadowing (Tab. 1). The city environment was further divided into the sparsely built-up areas which are typical for modern housing, industrial areas etc., and to areas with narrow streets, which is typical for the historical part of the city.

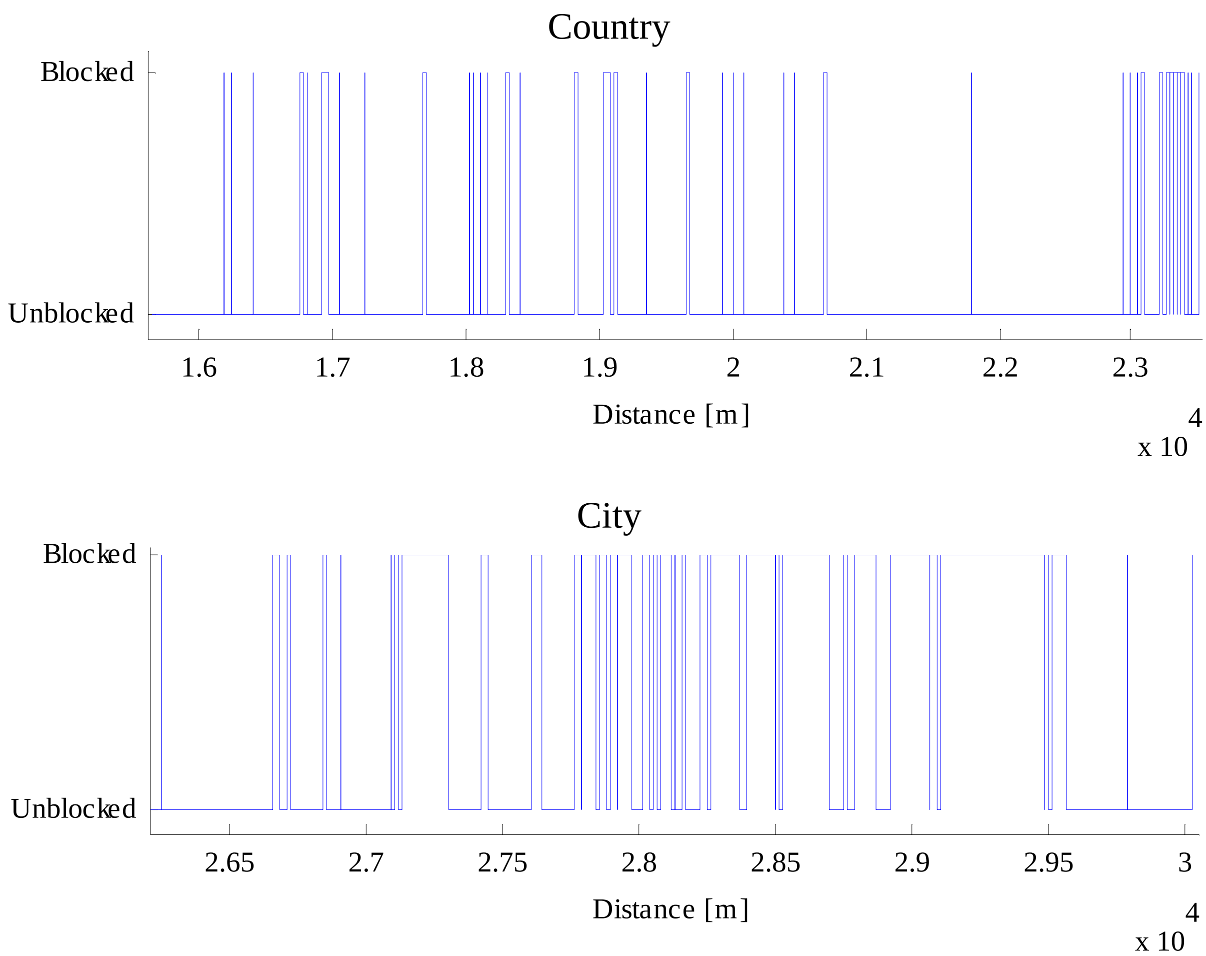

Fig. 5. Typical shadowing of the EGNOS IOR satellite

Tab. 1. Typical Parameters of the Mathematical Model

Environment	μ [m^{-1}]	λ [m^{-1}]	Visibility (π_0)
City – sparsely built-up area	0.06 – 0.1	0.02 – 0.04	60-80%
City – narrow streets	0.02	0.02	50%
Country	0.002 – 0.006	0.01-0.02	90-95%

The probability of the EGNOS message reception for various speeds of user motion was calculated on the basis of the mathematical model. The results were compared to the results obtained by a simulated ride through the given environment represented by the measured satellite shadowing process. Basic statistics, together with the statistics of the successful reception of at least one EGNOS message from *N* messages, are in Tab. 2.

Tab. 2. Typical Reception Statistics

Environment	Probability of the EGNOS message reception									
	N=1				N=2			N=3		
	Speed [m/s]									
	1	5	10	20	5	10	20	5	10	20
City – sparsely built-up area	0.66	0.64	0.61	0.57	0.66	0.64	0.61	0.68	0.69	0.68
City – narrow streets	0.52	0.48	0.43	0.38	0.53	0.48	0.44	0.57	0.55	0.53
Country	0.93	0.92	0.90	0.88	0.93	0.92	0.93	0.95	0.94	0.95

EGNOS message availability

The results of the second experimental session are discussed here. In virtue of experience from the previous experiments the country-type environment was further divided into undulating and flat areas.

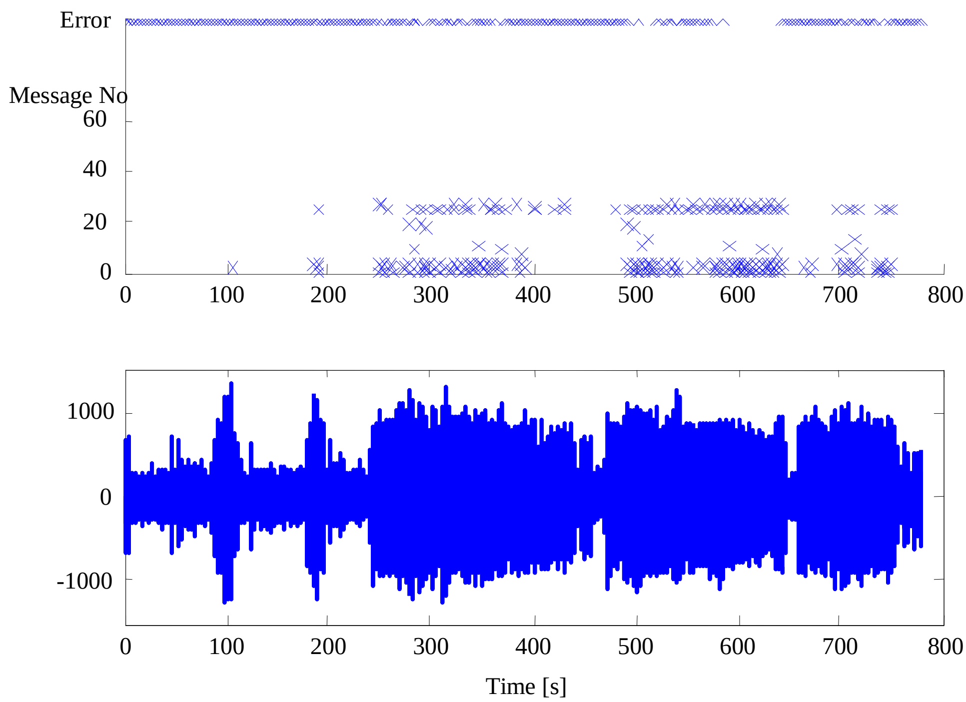

Fig. 6. Example of the EGNOS message reception and signal strength in cities – sparsely built-up area

An example of the experiment results is shown in Fig. 6. Series of the EGNOS message numbers received and decoded correctly and incorrectly can be seen, together with the signal strength for various environments. In city and dissected country areas we observed passages with total signal blockage, where reception and message decoding is impossible. The best reception of the EGNOS messages was naturally observed in flat country area. The observable short message dropouts can be caused by the vegetation around the roads, which blocked the signal in a relatively short time.

The results were statistically processed and the probability of the case that the time of reception of the message exceeded the given age was estimated. The ultimate ages of the partial EGNOS messages for air routes and precision approach navigation are specified in standard [5]. As far as we know, similar limits for land mobile navigation have not been defined yet.

The probability distribution of age of selected EGNOS messages is shown in Fig. 7. Messages No. 2 and No. 3 carry the fast differential correction and integrity information. These messages are usually transmitted at 6-second periods. The maximum age of these messages is 18 seconds for en route air navigation and 12 seconds for precision approach navigation. As an example of a message with a long transmission period message No. 18 was selected, which carries ionosphere grid data. This message is transmitted with a maximum period of 300 seconds. The maximum acceptable age of this message for both en route and precision approach navigation is 1200 seconds.

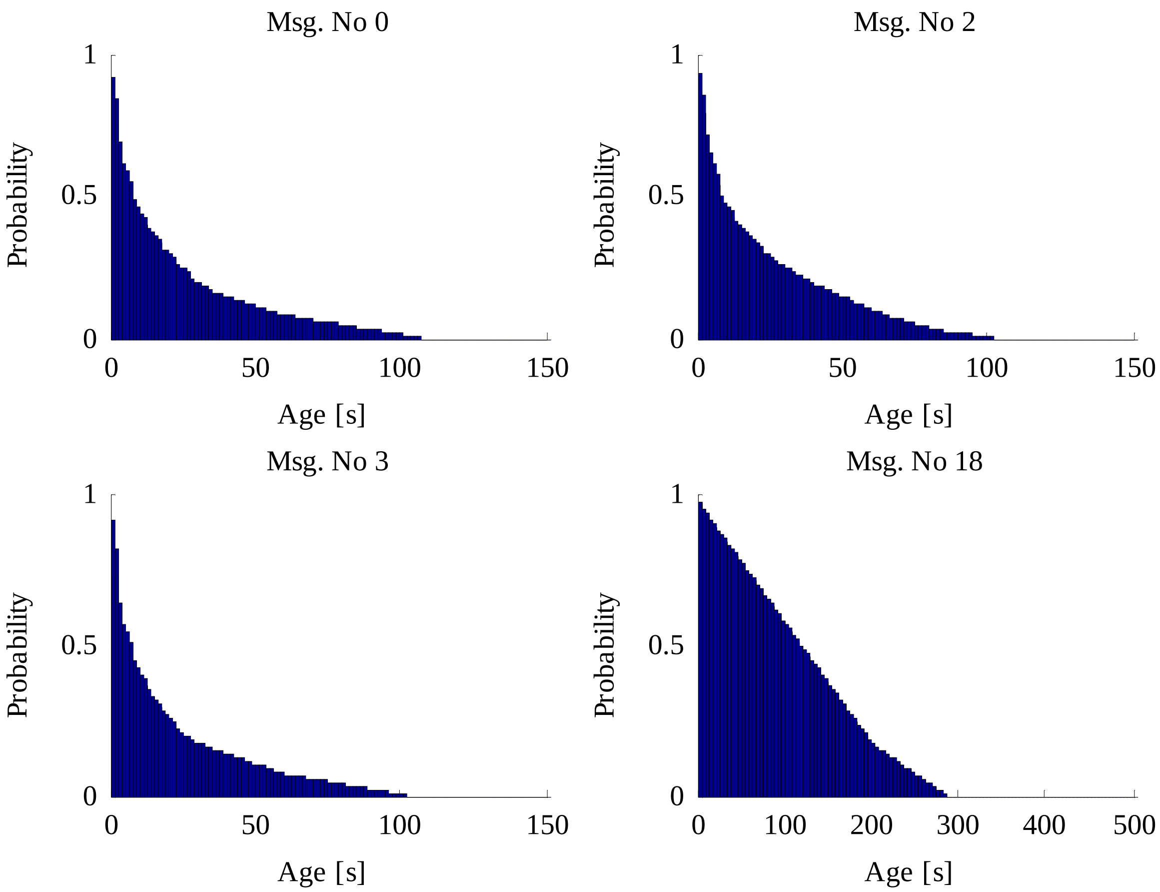

Fig. 7. Probability that the message exceeds given the age in the city – sparsely built-up area

If we use the criteria for EGNOS service availability defined for air navigation (due to a lack of similar criteria for land mobile navigation), it is clear that they are satisfied with a good level of service in some sections (or legs) of tracks only.

The research showed that the EGNOS service as specified in standard [5] is not available in the investigated environment in the entire area, but only in some areas.

It depends on the particular navigation application whether it requires full coverage or whether partial coverage is sufficient. The maximum acceptable age of the particular EGNOS messages for the land mobile navigation service should be defined for the future.

7. Software receiver for railway signaling system

We have developed a software receiver for a railway signaling system (Fig. 8), that is industry application of the Experimental GNSS Receiver. The railway receiver is a dual-frequency (L1, L2) receiver capable of GPS, EGNOS and Galileo reception.

The receiver is designed on a standard PCB board, 160 x 100 mm, and conforms to the industry environmental standard. The receiver analog and digital hardware is designed by progressive low voltage technology.

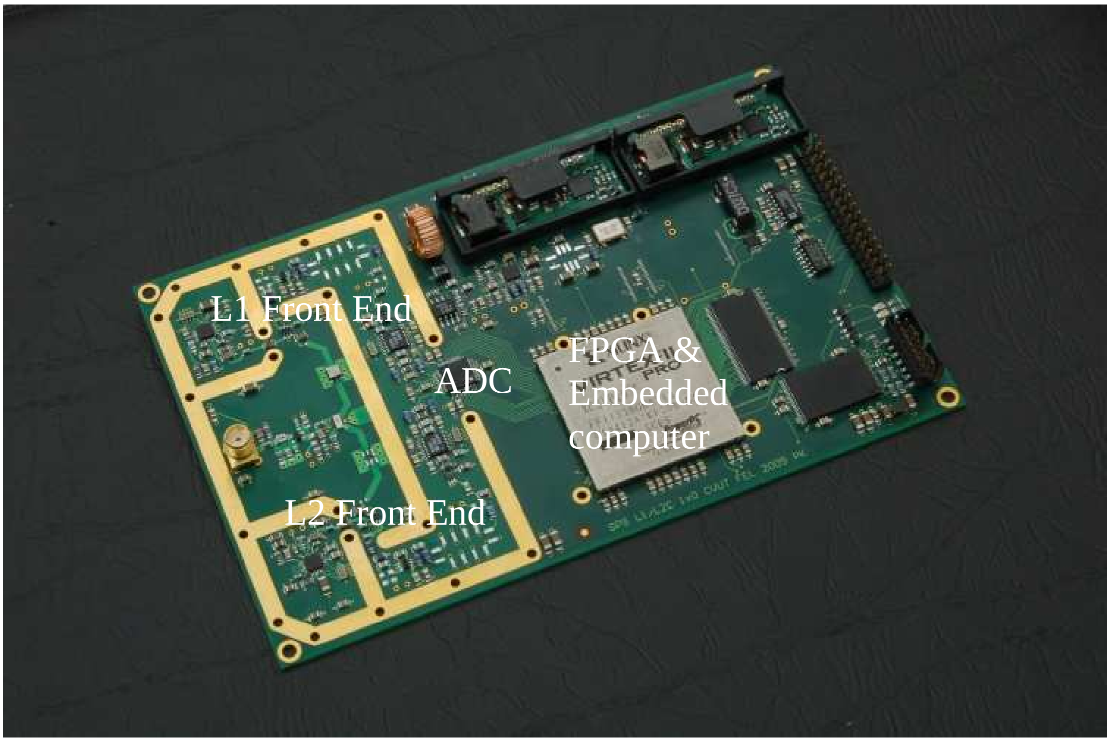

Fig. 8. Software GNSS receiver for railways

6. Conclusions

The SDR is modern architecture which is widely used for designing GNSS receivers not only for research and educational purposes, but some software GNSS receivers are integrated in mass production equipment because of their low cost.

SDR receivers are very flexible, which enables upgrading the receiver signal processing and implementing new navigation signals and systems by new software download only.

Our research is oriented to the GNSS SDR. We successfully caught the trend of implementation of software radio to satellite navigation in 2000 and since then, we have contributed by our research to the development in this new field. We developed the GNSS SDR receiver for research and development purposes.

The Experimental GNSS Receiver was used for investigation of the availability of the EGNOS system for land mobile users. In the theoretical part of this project we developed an EGNOS channel model for land mobile use. In the experimental part we developed special signal processing for the experimental receiver that enabled us to realize mobile experiments with the EGNOS signal to determine the proposed model parameters for the particular environment and verify the propagation model. We also implemented an optimal receiver for mobile reception of the EGNOS navigation data.

Research showed that the EGNOS service as specified in standard [5] is not available in the investigated environment in the whole area, but only in some areas.

It depends on the concrete navigation application whether it requires full coverage or whether the particular coverage is sufficient. The maximum acceptable age of the particular EGNOS messages for the land mobile navigation service should be defined for the future.

The results of our research carried out in 2005-6 correspond well with the official EGNOS policy [17]. In 2004, when we started our research, the official ESA opinion of EGNOS was that EGNOS was fully applicable for land mobile users. The aim of our research was to verify this assumption and to find the method of receiving and processing the signal for land mobile use. In 2006 and 2007 the ESA website [17] provided information about the projects of distribution of the EGNOS data via alternative channels to increase service availability for land mobile users.

Other activity concerning the software receiver and its application in GNSS has been:

- Development of the software GPS/EGNOS/Galileo receiver for railway signaling systems.
- The 6th Framework GARDA project, where we participated in the development of the SDR receiver for Galileo.

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PhD. (Dr.) 1998, Czech Technical University in Prague, Faculty of Electrical Engineering

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Professional Positions:

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Technical Skills:

Radio Engineering, Signal Processing, Digital Signal Processing, Communication and Navigation Systems, Satellite Navigation Systems, Radio Navigation, Avionics, Software Radio, Programmable Logic

Teaching Activity:

Radio Systems (RSY), Radio Systems 1 (RS1), Radio Systems 2 (RS2), Air Traffic Control (RLP)**,** Communication Technology – Radio Systems (KTR), Radio Function Blocks (RFB)

Publications:

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Professional Experience

- Development and testing of aviation communication and navigation instruments
- Radio frequency circuit design
- Receiver system planning and receiver design
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