Universal Front End for Software GNSS Receiver

Pavel Kovář, Petr Kačmařík, František Vejražka
Czech Technical University in Prague, Faculty of Electrical Engineering

BIOGRAPHY

Pavel Kovář received MSc. and PhD. degrees of Radio Engineering from Czech Technical University in 1995 and 1998, respectively. From 1997 to 2000 he worked as an avionics system designer in Mesit Pristroje. Since 2000 he has been with the Department or Radio Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague as assistant professor (from 2000 to 2007) and associate professor since 2007. Since 2000 he has worked on the software GNSS receiver development. He participated on several research projects like GARDA, Participation of the Czech Republic on Galileo project, etc.

Petr Kačmařík received the MSc. degree in Electrical Engineering and Ph.D. degree in Radioelectronics from the Czech Technical University in Prague, in 2002 and 2009 respectively. Since 2006 he works as assistant professor at Czech Technical University. His main professional interests are satellite navigation, digital signal processing, signal processing algorithm implementations and their simulations. Dr. Kacmarik participated on all main projects which were held on the Department of Radio Electronics since his PhD study (2002) and his later work affiliation at the department, especially: the project of Ministry of Transport of the Czech Republic (2000 – 2006), the Sixth Framework Programme GARDA (2004 – 2006).

František Vejražka is the full professor of radio navigation, radio communications and signals and systems theory at the Czech Technical University in Prague. He was appointed the vice-rector of the University in 2001.
His professional interest is in radio satellite navigation where he participated on the design of the first Czech GPS receiver (1990) for the MESIT Instruments factory. His team was the provider of the experimental DGPS reference station in nineties. They prepared experimental receivers for Galileo, GPS and GLONASS based on software radio concept and participated on European 6-th Frame Program project GARDA.
Prof. Vejrazka is the former president of the Czech Institute of Navigation, Fellow of the Royal Institute **of** Navigation in London, member of the Institute of Navigation (USA), CGIC-IISC, IEEE, member of Editorial Board of GPS World, Editorial Board of Inside GNSS, etc.

ABSTRACT

The paper deals with the design of the high performance front end for GNSS software receiver. The various front end architectures are analyzed. The design of the complete analogue signal processing chain i.e. multi frequency antenna LNA, RF filters and configurable receiver for civil GPS and open Galileo signals are presented in the paper. The front end is based on the direct conversion receiver architecture. The frequency range of developed front end covers all L band GNSS signals. The bandwidth is controlled in range 8 ÷ 66 MHz.
The antenna amplifier design is complicated by frequency proximity of the GPS L2 and Galileo E5 signals, the non-conventional signal splitting had to be used.
The front end is designed to be able to accept high level out band and undesired and interference signals.
The paper presents test results of the main parts as well as the verification results on the live Galileo E5 signals.

1. INTRODUCTION

The software radio is modern radio receiver and transmitter concept, which is widely, used for its flexibility and versatility in many radio systems. The software receiver is not only software for radio signal processing, but also a radio reconfigurable and programmable hardware, which usually consists of analogue part and digital processing part. The software receiver for processing of the real signals always consists of an analogue part (RF front end) because of the received signal analogue nature. The signal in the output of the front end is converted to the digital domain and processed in a programmable digital signal processor. The performance and versatility of the software receiver depends on the performance of the receiver hardware and on the software.
The software receiver is widely used for GNSS receiver design for its flexibility and for ability of the

receiver upgrade to new signals and systems especially European Galileo and Chinese Compass.
The aim of this paper is to describe high performance universal front end for software GNSS receiver, which was developed at the Czech Technical University.

2. MAXIMUM RQUIREMENTS ON THE GNSS SOFTWARE RECEIVER FRONT END

The requirements on the ideal front end for software GNSS software receiver is as follows:

1. Frequency range from 1164.45 MHz (GPS L5, Galileo E5a) to 1605.375 (GLONASS L1 channel 6). The receiver should be capable to process any known L band navigation signal. The tuning step should be small fraction of the minimum bandwidth.
2. Reconfigurable bandwidth from 1 MHz to 90 MHz. The front end should be reconfigurable for processing of narrow band GNSS signals like GLONASS L1 of bandwidth approx. 1 MHz to extremely wideband signals like Galileo E5 of bandwidth approx. 70 ÷ 90 MHz.
3. Low noise figure (< 1dB).
4. No signal distortion. The front end should fully comply with the condition of the no signal distortion transmission, i.e. the amplitude response of the front end for desired signals should be constant and phase characteristic should be linear. The front end should not produce non-linear distorted signals, i.e. the one decibel compression (IP1) and third and higher intercepts point (IP3) should be very high. The front end should operate in linear condition even if the high levels in band and out band signals are presented.
5. Total suppression of the out of band signals.
6. Low power consumption.
7. Software control of all front end parameters.

The multi frequency software receiver also requires wideband or multi frequency antenna.
Our analysis of the universal front end therefore should cover an antenna low noise amplifier and an antenna filters.
The full fulfillment of these contradictory requirements are very difficult, some compromise must be admitted.

3. FRONT END ARCHITECTURE

This paragraph analyses possible architecture of the GNSS front end for the software receiver. These receiver architectures are:

1. Tuned radio frequency receiver (TRF),
2. Superheterodyne receiver,
3. Direct conversion receiver.

The **tuned radio frequency receiver** consists of a selective amplifier which processes signal from the antenna. No frequency conversion is implemented. The signal should be converted to the digital domain directly on the carrier frequency. This type of the receiver has problem with selectivity because of problematic realization of the high selectivity filters on RF. The realization of the frequency agile filters is very problematic; controlled bandwidth filter is not realizable.
An ADC (analogue to digital converter) of such receiver should directly process gigahertz frequencies. The power consumption and cost of such ADC are very high. There are high requirements on the extremely low jitter or phase noise of the sampling signal because of the degradation of the signal to noise ratio on the ADC output.
There is no technology for realization of the linear phase filters on these frequencies. The much wider filters therefore must be used for fulfillment of the non distortion reception.
The **superheterodyne receiver** solves some problem of the tuned radio frequency receiver. The received signal is converted to the fix intermediate frequency. This intermediate frequency signal is more easily filtered and converted by the ADC. In addition, the filter technologies like SAW (surface acoustic waveform) which fully satisfy the conditions for non distortion processing are available. The control of the receiver bandwidth can be realized for example by the bank of switched filters, but this solution is very expensive.
This radio receiver architecture is widely used for the design of high performance professional and mass market receivers not only in GNSS but also in communication systems and consumer electronics.
The **direct conversion receiver** is receiver which directly converts received signal to the baseband. The entire baseband representation of the radio signal is so called complex envelope signal. The direct conversion receiver therefore has two branches, one for processing of the real part (I) and second one for processing of the imaginary part (Q) of the complex envelope. The both signals are filtered in low pass filters. These low pass filters can be realized by the monolithic technology in the chip. The bandwidth of such filter can be digitally controlled. The phase characteristic of integrated low pass filter is not principally linear because of the minimal phase circuits, but the modern technology enables to manufacture filter with small phase and amplitude distortion.
The problem of direct conversion receiver is in realization of the high gain DC amplifiers because of DC biases and 1/f semiconductor noise. This problem is partially solved by utilization of the DC biases compensation technique. This technique suppresses or distorts signals on low frequencies. These frequencies are also demoted by the amplifier noise.
Described distortion of the direct conversion receiver has only negligible impact on the tracking performance of the GNSS receiver because this distortion disturbed spectral component around the carrier frequency only. The crucial impact on the GNSS receiver performance has the spectral components very fare from the carrier frequency on the other hand. This is why the BOC modulated signals has only adjacent spectral lob on this frequencies for example.

The direct conversion receivers are very popular recently because of the relatively good performance, high flexibility, low bill of materials and low price because nearly all parts of the receiver can be integrated to the chip.

4. ANTENNA AMPLIFIER

The antenna amplifier is significant part of the GNSS front end. The noise figure of this amplifier has crucial impact to the noise figure of the receiver. The RF designer has to solve problem what to place first, low noise amplifier (LNA) or frequency filter.
The first choice is featured with the excellent noise figure, but the LNA must process all signals received by the antenna radiation element including out band signals. The dynamic range of the LNA should be very high to be able to process signals without intermodulation, cross-modulation and other distortions. The power consumption of such LNA is therefore very high.
The second choice is featured by the slightly worse noise figure because of the insertion loss of the frequency filter, but this frequency filter attenuates all out of band signals. The dynamic range of the LNA can be much lower then in the first case. The power consumption of the LNA is then much lower.
The next problem is design of two or multiple frequencies antenna. The signal has to be split and processed in multiple frequencies filters. In the antenna output, the signals should be combined or multiple antenna feeders should be used. The signal splitting can be realized by the frequency diplexer or n-plexer for n frequencies antenna. These frequency n-plexers operates on principle that frequency filters reflect the out of band signals. This splitting technique can be easily used for processing of no frequency overlapped signals. The amplitudes of the overlapping signals are distorted.
The next splitting method uses wideband power splitter (divider), for example Wilkinson power divider. The insertion loss of such solution is given by the number of output ports because the input power is uniformly divided among ports. The insertion loss of ideal three output ports power divider is 4.77 dB, for example. This splitter is sensitive on impedance mismatching of the output ports, but it causes lesser distortion then mismatching in the frequency n-plexer.

5. UNIVERSAL GNSS FRONT END DESIGN

This paragraph describes the universal GNSS front end for software receiver developed at the Czech Technical University.

5.1. Design requirements definition

Firstly, we define basic requirements on our front end. To meet the maximum requirements specified above (par.2) can be demanding due to technical feasibility and extreme costs. Therefore we reduced our requirements on:

1. Frequencies L1, L2 and complete L5
2. Low Noise Figure (<2 dB)
3. High dynamic range
4. Low distortion

5.2. Antenna Amplifier

We originally considered applying agile antenna filter in our front end, but this technology is not accessible for us and the commercial filters are very expensive. Therefore, we reduced our requirement and we decided to use application specified ceramic filters.
The original concept assumed to process Galileo E5 and L2 signals in a single channel. But its design and manufacture by the ceramic resonator technology is problematic because the L2 frequency would be distorted. The L2 and E5 signals have to be processed in separate channels therefore.
The other complication appeared with the splitting of the signals because the Galileo L5 and GPS L2 frequency bands are overlapped. The minimal E5 filter upper cut off frequency is 1191.795 + 70/2 = 1226.795 MHz and maximum L2 filter lower cut off frequency is 1227.6 – 20/2 = 1217.6 MHz.
The frequency triplexer for splitting of these signals (L1, L2, E5) cannot be used due to the spectra overlapping. This problem was solved by application of the Wilkinson power divider and its insertion loss was compensated by the high dynamic range wideband amplifier.

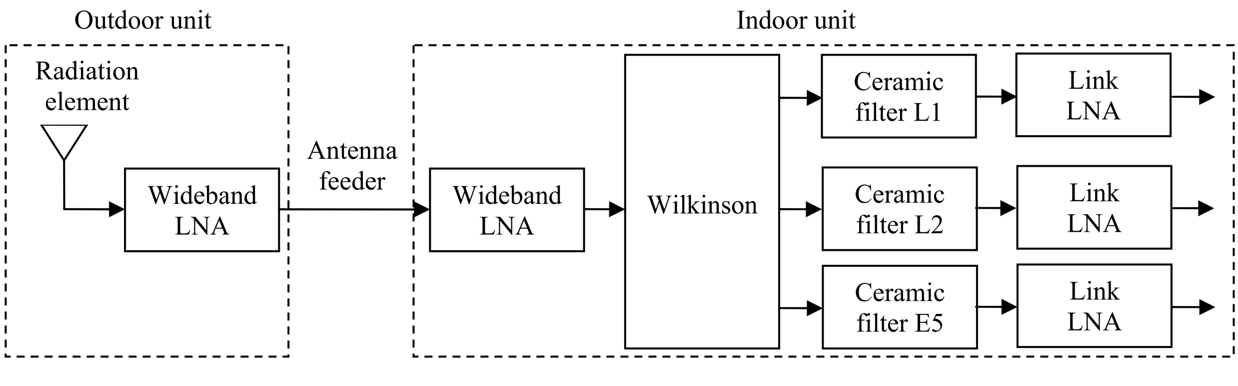

Fig. 1 Antenna amplifier block diagram

The block diagram of developed antenna amplifier is in Fig. 1. The amplifier consists of outdoor and indoor units. The outdoor unit is designed as wideband, low noise and wide dynamic range amplifier. The signal from its output is fed to the indoor unit by a single coaxial cable. The indoor unit consists of the same wideband amplifier as indoor unit and of the Wilkinson three output ports power splitter, bank of ceramic coaxial resonators filters and link amplifiers.

5.3. Wideband LNA

The fundamental problem of the wideband LNA design is transistor selection. We selected medium power GaAs pHEMT transistor ATF-53189 by Avago Technologies, which is developed for wideband low noise amplifiers of cellular base stations. The transistor impedance matching (Fig. 2) is designed from lumped elements. The transistor parameters are in Tab 1.

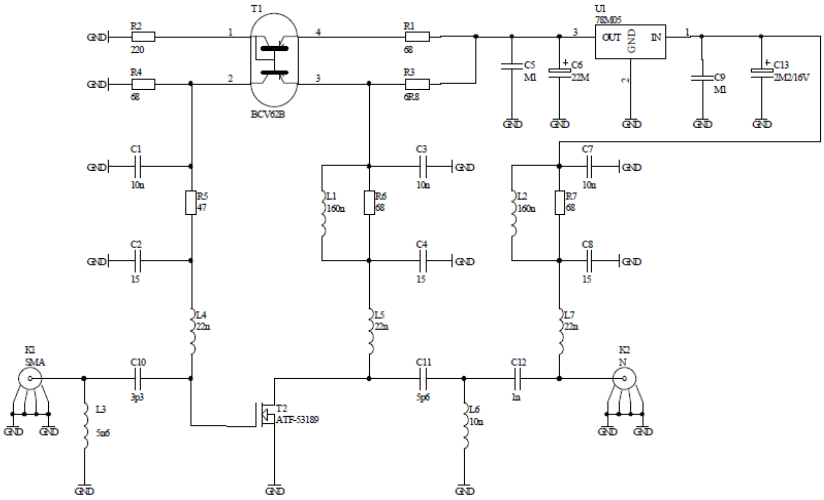

Fig. 2. LNA

Tab 1. ATF-53189 features on 2 GHz, 4V, 135 mA

IP1	23 dBm
IP3	40 dBm
Noise Figure	0.85 dB
Gain	15.5 dB

The realized amplifier is in Fig. 3. The measured gain and noise figure is plotted in Fig. 4. The measured IP1 of the developed LNA is 21.3 dBm on frequency 1.5 GHz.

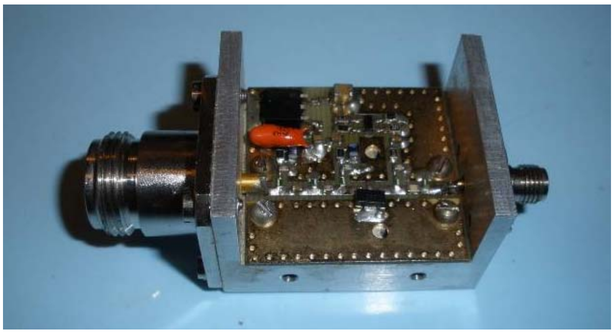

Fig. 3. Wideband LNA prototype

The snapshot of the indoor unit is in Fig. 5. The frequency responses and phase characteristics of particular channels are in Fig. 6 - 8. The LNA power supply voltage is 12V. The voltage is internally stabilized to 5V by linear voltage stabilizer for transistor powering. This solution increases LNA power consumption, but it does not produce interference like switched stabilizers. The power consumption of the wideband LNA is 2.2W, but approx. 60% is dropped on the stabilizer.

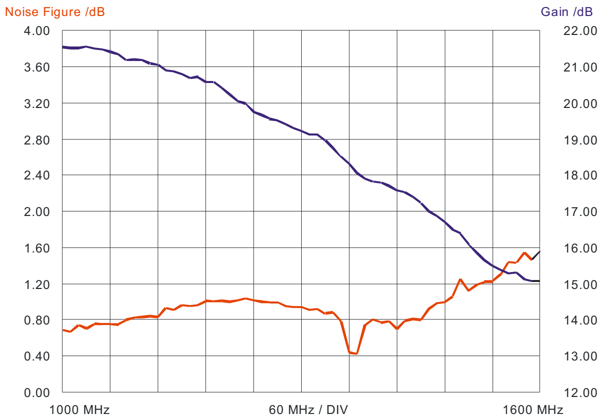

Fig. 4. Wideband LNA gain and noise figure vs. frequency

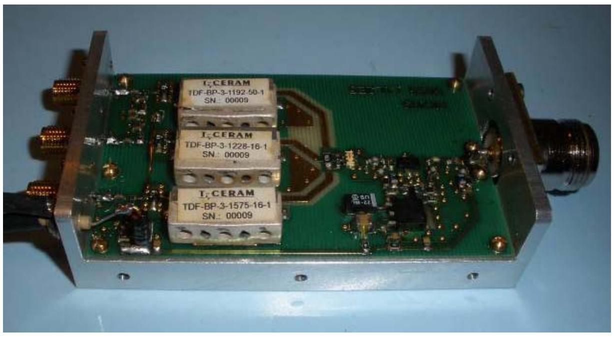

Fig. 5. Indoor unit prototype

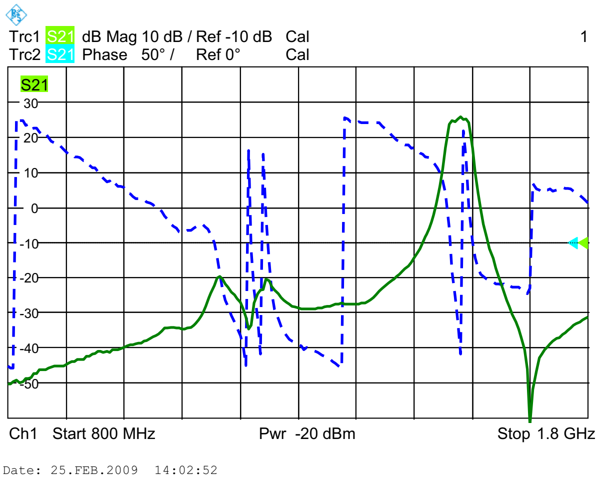

Fig. 6. Indoor unit frequency response, channel L1

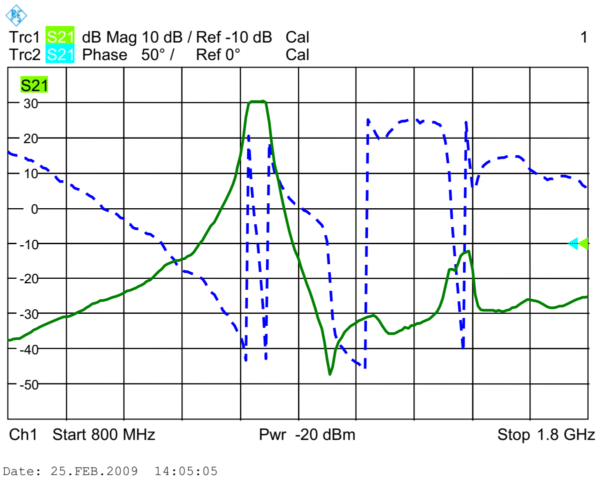

Fig. 7. Indoor unit frequency response, channel L2

Tab 2. MAX 2118 features

Frequency range	850 ÷ 2175 MHz
Bandwidth	8 ÷ 66 MHz
Input level	-77 ÷ 16 dBm
Gain control	93 dB
Noise figure	10 dB

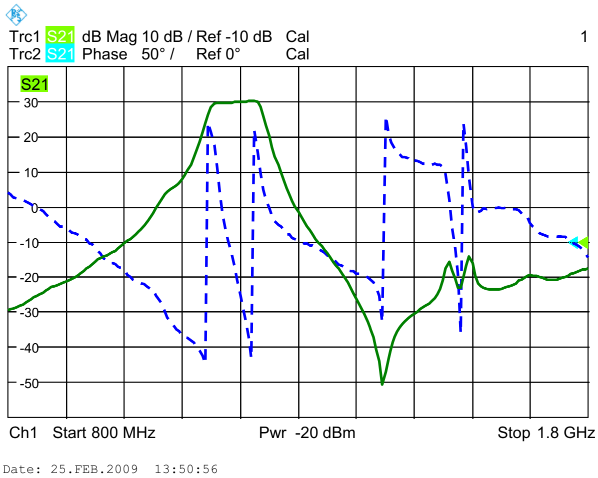

Fig. 8. Indoor unit frequency response, channel L5

5.4. Front end

The direct conversion receiver architecture was chosen for the front end design because of availability of the fully programmable L band monolithic receiver MAX 2118 by MAXIM Fig. 10. This integrated circuit integrates the whole receiver including local oscillators, PLL, LNA, mixers, programmable low pass filters and programmable gain amplifiers. The recommended operation circuit is used. The receiver is controlled via I2C bus. The main features are in Tab. 2.

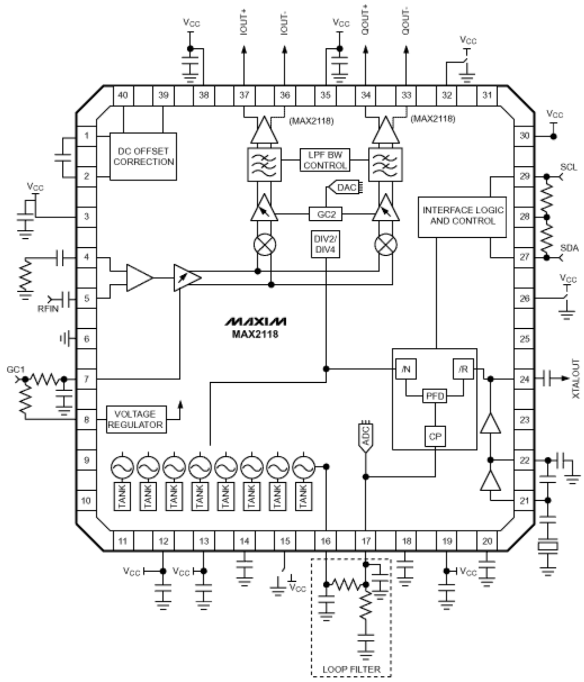

Fig. 10. MAX 2118 typical operating circuit

The PCB board prototype with the receiver front end, ADC for ML506 development board by Xilinx is in Fig. 11 and 12.

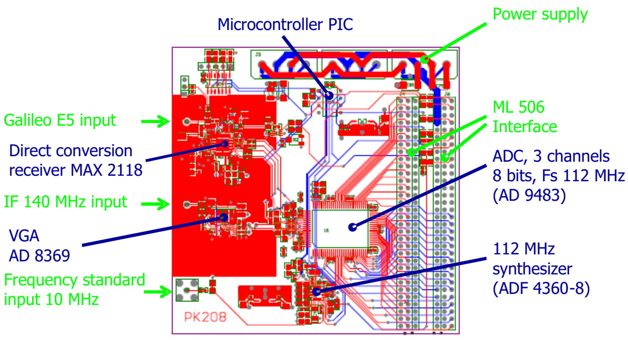

Fig. 11. Receiver front end

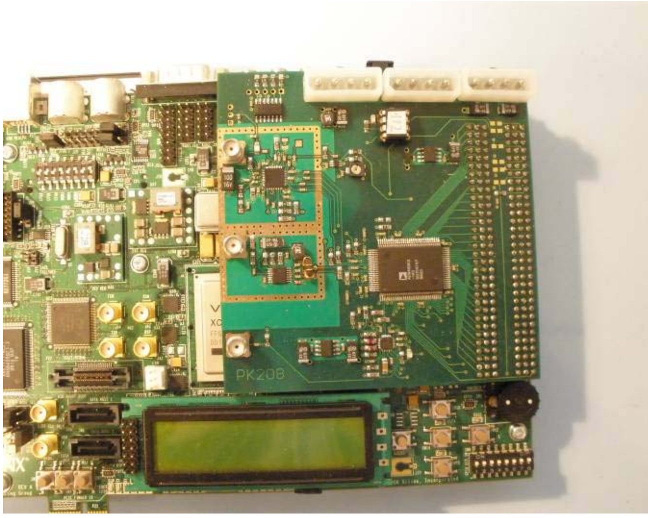

Fig. 12. Receiver front end prototype

6. TEST RESULTS

The developed universal front end for GNSS software receiver was properly tested and measured in laboratory and as a part of a real receiver. Some laboratory test results are introduced in the above paragraphs. This paragraph describes selected test results in the real receiver. The front end was used for reception of the Galileo E5 signal of the test Giove A and Giove B satellites. The measured tracking errors are in Fig. 12.

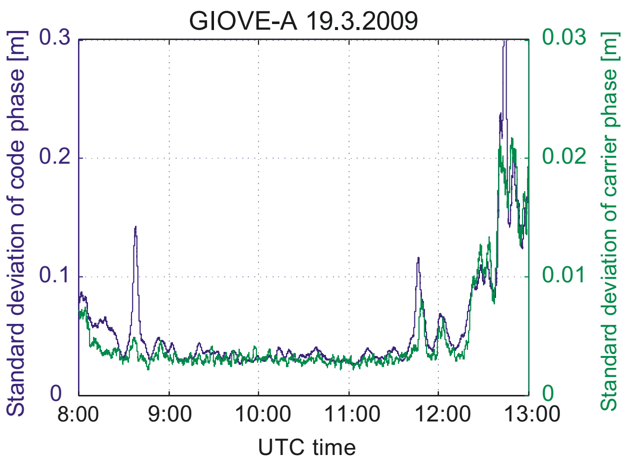

Fig. 12. Code and carrier phase tracking error, Giove A, E5

The receiver operates properly even if the antenna is placed several tens meters from the cellular phone base station. The intermodulation distortion of the signal caused by the based station was not observed by a spectral analyzer.
The real measurement, which was performed with both Galileo experimental satellites, gave very low pseudorange and carrier phase noise Fig. 12. The pseudorange noise didn't exceed 5 cm for reasonable satellite elevation. The phase measurement noise was ten times lower, i.e. lesser than 5mm.

7. CONCLUSION

We described architecture of the universal front end for software GNSS receiver developed at the Czech Technical University. The developed front end with the three frequencies antenna amplifier complies with our design requirements specification. The front end features with the low noise figure, wide dynamic range and minimal distortion.
The disadvantage of it is high power consumption, 2.2W of the outdoor, 2.6W of indoor amplifier units and 1.2W of the direct conversion receiver.
The test results demonstrate that the front end can be used in high performance GNSS software receiver and in addition it is capable to process the most complicated GNSS signal such as the Galileo E5 Open Service signal.
We successfully solved several technical problems, for example the E5 and L2 signal splitting, during the development

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