Augmentation Methods for GNSS Integrity and Precision Enhancement in Difficult Environment

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BIOGRAPHY

Pavel Kovář received M.Sc. degree (1992) and Ph.D. (1996) degree in electrical engineering at the Czech Technical University (CTU) in Prague. He worked as a senior design engineer in communications company Mesit Uherske Hradiste and now he is working on his associated professor degree. He is involved in the design of advanced GNSS signal processing algorithms and its implementation into software receiver architecture.

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ABSTRACT

The topic of the paper is to describe influences of the difficult environment to the GNSS and SBAS signals and consequences for signal processing. At first, the issues related to signal reception in difficult environment are discussed, namely signal attenuation and shadowing, multipath propagation and effects related to user receiver movement. The satellite line of sight shadowing influence to signal reception is discussed for various environments together with proposed shadowing model. The model is derived from two state Markov model. The experimental measurements of mobile reception of EGNOS signal has shown the need of supporting SBAS signals in several environment by complementary transmission. Such concept of supporting system with data transmitted by separate channel is discussed in the paper both for DGNSS and SBAS case. The possibility and analysis of use of Internet for real time distribution of augmentation data is presented in the paper, namely questions of data latency and augmentation influence to user position in difficult environment.

INTRODUCTION

The satellite navigation systems are now frequently used in wide range of applications and environments. The plan of combination of in the future available Galileo system with modernized GPS and restored GLONASS will bring to the sky more than 60 satellites whose ranging signal can be used. The concept of Global Navigation Satellite System (GNSS) together with the development of the integrated chipsets for all systems for mobile equipment open broad spectrum of possible applications. It can be various Location Based Services (LBS), for example hazardous material transport monitoring, public transport services optimization and synchronization, position based lock of the classified data or position based advertising, or incorporation of GNSS to position determination for E112 emergency calls. A lot of present and future mobile phones and handhelds will have built in navigation receivers intended for personal oriented LBS use.

All the mentioned cases are characteristic by one common attribute: navigation receivers are supposed to work under various circumstances, even under the difficult conditions or indoors. For example journey passing through terrain cuts or urban canyons, inside of the store-house, high-rise building or roofed station, virtually any place where the position demand occurs. The users of all applications expect the stable quality of LBS no matter to the environment the service is used in. That's why the use of GNSS in difficult environment brings new challenges in the GNSS signal processing and receiver design. Moreover, safety critical applications need high level of GNSS integrity information and highest possible position information enhancement. These requirements are usually provided by augmentation systems, either on local basis or with the global coverage. Such system is EGNOS, the Satellite Based Augmentation System (SBAS), providing enhancement and integrity information for GPS and GLONASS.

GNSS IN DIFFICULT ENVIRONMENT

The search in two domains, frequency and time (delay), which brings estimates of the Doppler frequency and code delay for GNSS signal acquisition, is quite well known for non-complicated outdoor environment. In case of good visibility to the sky there are several strong satellite signals present and the tasks of acquisition, tracking, and position computation are relatively easy.

The other situation is for the case of user receiver location in difficult environment, i.e. urban canyon or indoors. The signals coming from the satellites are obstructed by foliage, steep slopes, building walls, and other structures. The signal that can be used by the user receiver in such environment is mostly consisted of strongly attenuated direct signal and reflected (and/or scattered) signals. The receiver has to deal with signal attenuation and multipath effects affecting its performance [1].

The signals coming from direct path are already weak, about –160 dBW (for example GPS C/A code L1 signal is specified by IS-GPS-200 to arrive to the user receiver at the Earth surface at not less than –158.5 dBW). The satellite signal is in case of signal obstruction further attenuated according to the nature of the obstructing material. For example the plywood wall attenuates GPS signal by about 2.3 dB, while cinder and concrete induced attenuation is ten time higher. The wooden house then for instance performs attenuation of about 10 dB while residential house with brick walls brings attenuation of 20–25 dB. The similar situation is in outdoor difficult environment represented by dense foliage because the vegetation canopy is highly variable depending on the type of foliage, year season, meteorological conditions etc. That's why the receivers have to deal with signal acquisition and tracking at levels form –160 dBW to –190 dBW. If we consider present sensitivity of the consumer grade receivers, having sensitivities in range –165 to –189 dBW, the above mentioned tasks related to signal acquisition process are rather complicated.

The other related value for weak signals acquisition and tracking is SNR (power of the signal to power of the corresponding noise) or even more often Carrier to Noise Power Density C/N0, the ratio of the power level of a signal carrier to the noise power in 1 Hz bandwidth. The acceptable C/N0 is a key parameter for evaluation of the GPS receiver performance. The signal strength of –160 dBW corresponds to C/N0 of 41-45 dBHz. Nominal C/N0 values what should be classical GPS receivers able to work with are in the 33 to 35 dBHz range.

The signals are acquired and tracked by correlation and integration usually in interval in units of milliseconds. In case of attenuated signal, the integration time can be extended to get required processing gain to achieve sufficient SNR because for coherent integration the noise bandwidth is reduced in inverse proportion to the integration time. However, the extension of the integration time is affected by the problem of GPS data bits width of 20 ms. If the integration period goes through the boundaries of data bits the integration is affected and SNR drops. One of the commonly used solutions is non-coherent integration with squaring the signal to remove BPSK data. However the squaring is performed also on the noise resulting in presence of squaring loss affecting processing gain. The squaring loss is also the reason for rapid increase of non-coherent integration time in case of received signal level drops. The mechanism of the non-coherent integration time extension to achieve sufficient SNR is provided under a basic assumption that the Doppler error remains constant or small enough during the whole integration period. The Doppler error caused by instability of the receiver frequency standard and receiver antenna movement can then limit integration time due to caused phase changes. If we assume the Doppler error caused by satellite movement resolved, the other changes in the spectrum of the correlator output can then be caused by user receiver antenna movement, reaction of the receiver frequency standard to the movement, jerk stress, and natural instability of the frequency standard. The typical affection of carrier wave signal and spectrum by indoor user movement is shown at Fig. 1 and Fig. 2 [2].

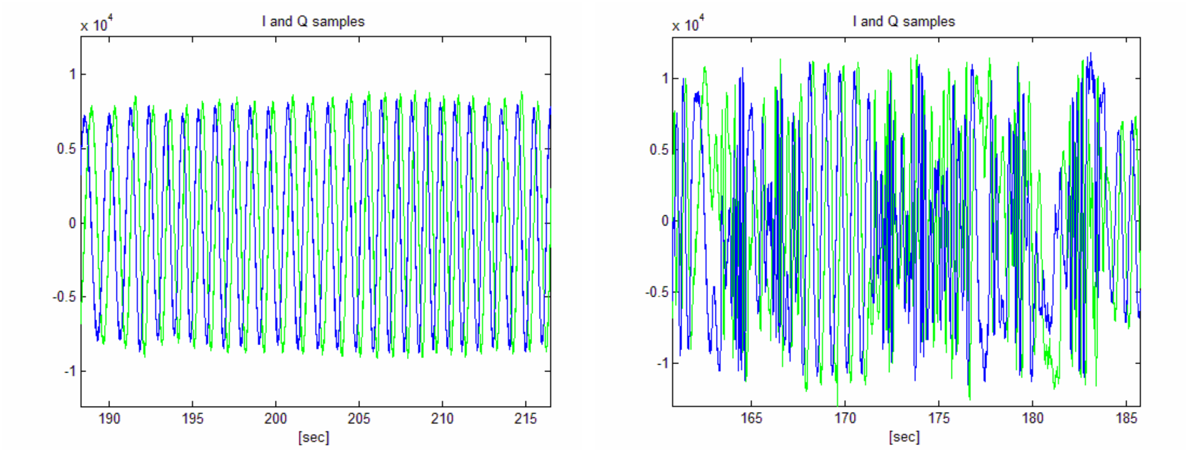


Fig. 1. Inphase (blue) and quadrature (green) output samples of GPS L1 correlator for measurement without user move (left) and measurement affected by user indoor movement (right).

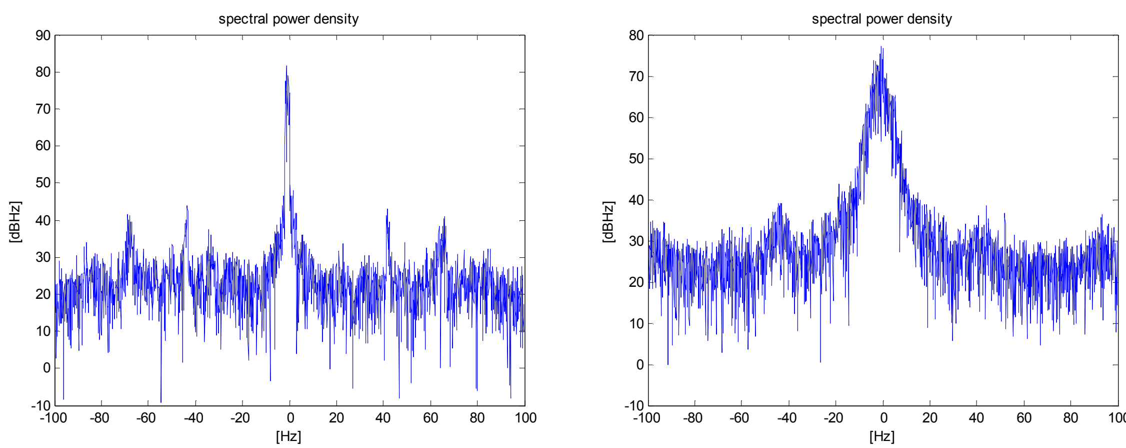


Fig. 2. spectral power density for measurement without user move (left) and measurement affected by user indoor movement (right).

If we consider bandwidth of the DLL filter in range of units of Hz suitable for multipath mitigation (for example bandwidth used for narrow correlator concept is about 2 Hz), we can see the possible loss of SNR due to user movement because of the notable widening of the power spectral density main lobe together with drop of its level. The wider bandwidth of the loop filter means raise of the noise and thus mentioned decrease of the SNR. Moreover, the user movement produced wider spectral power density is related to small but quick changes of the Doppler shift that has to be taken into account during frequency/delay search in acquisition phase.

USABILITY OF AUGMENTATION FOR GNSS PERFORMANCE ENHANCEMENT

In previous discussion we were assuming stand-alone GNSS receiver not considering advanced acquisition techniques, for example Assisted GNSS. The use of AGNSS assumes existence and particularly the accessibility of the data for provision of supporting information, e.g. initial approximate position of the receiver, the decoded satellite ephemeris, and clock information. After that, the reduction the searched space or increase of integration time by data removal and thus possibility of processing weaker signal levels is possible. Such system usually uses various levels of augmentation according to the particular application and available supporting infrastructure.

Another use of augmentation signals can be used for enhancement of GNSS based LBS performance (integrity, precision, availability). Typical examples are Satellite Based Augmentation Systems (SBAS) providing corrections for increase of precision or additional data for securing integrity of the system for safety-of-life applications. Both kinds of augmentation rely on provision of supporting data in addition to simple GNSS ranging signal.

The significant phenomenon that is often present in satellite mobile applications is effect of rapid variations of signal availability due to frequent line of sight shadowing. This effect affects performance of GNSS by the need of reaction to loss and presence of signal and thus executing the re-acquisition task. We have investigated such problem for the case of EGNOS SBAS signal availability to the mobile user in difficult environment. The EGNOS signal was used because of convenient resolving of satellite movement contribution to the Doppler shift thanks to GEO satellites used by this system. The shift caused by satellite could be considered to negligible and we could concentrate on impacts of user movement in various environments. The results of such analyses and measurements described in following section can provide a significant help in decision when to rely solely on the conventionally distributed SBAS signal and when is necessary for the sake of integrity and performance to use another transmission method.

EGNOS signal shadowing in land mobile applications

Mobile channel models of satellite systems are based on general channel models. The satellite mobile channels differ from terrestrial mobile channels in the fact that the direct signal path for mobile channels is blocked only in the close surrounding of the receiver antenna. The fluctuation of signal strength caused by the medium-term fading is then not characterized by log-normal distribution known from terrestrial channels but rather by its discrete states (open, closed). Fig. 3 shows block scheme of the model of mobile satellite channel with frequency flat fading [3]. The channel is characterised by its two states: open (unblocking), closed (blocking). The state open means that direct path signal is not blocked. In this state, the flat fading is modelled by the Ricean random process. The parameter c expresses ratio of direct path signal power to power of diffracted and reflected signals. The flat fading in the channel state closed is modelled by the multiplicative random process with log-normal distribution with parameters μ and σ. The mechanism of the opening and closing of direct path is usually modelled by Markov chain for the discrete time model and Markov process for the continuous time, respectively.

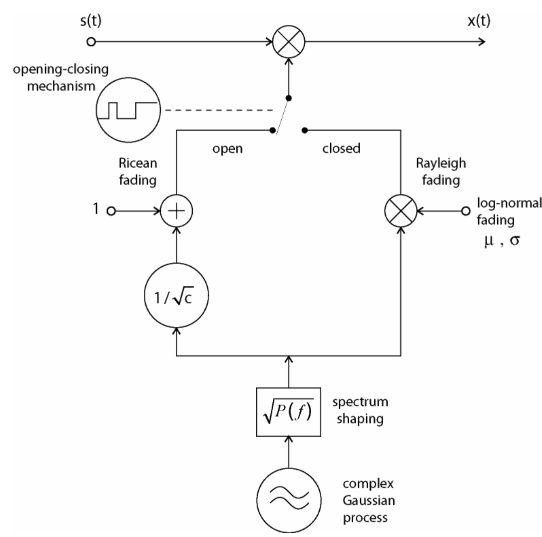


Fig. 3. Model of a frequency-flat fading satellite channel

Mobile satellite channel at the frequency 1.5 GHz can be considered as a frequency flat fading channel for narrow bandwidth only. In case that bandwidth is wider than 30 MHz the delay of the reflected signals has to be taken into account which complicates the corresponding channel model [4].

First step to successful reception of the EGNOS message is correct and fast detection of the EGNOS signal. The advantage of the EGNOS is its use of geostationary satellites for signal transmission. Thus the signal is not affected by the Doppler offset of the carrier frequency caused by the movement of the satellite. The frequency offset of the received signal is then caused by user receiver movement and inaccuracy of the receiver clock source. The sources of errors and the related frequency offsets are summarised in the following table.

Sources of Errors	Max. Frequency Offset [Hz]
Satellite movement	0
User movement (max. radial velocity 72 km/h)	100
Inaccuracy of the receiver clocks 10-7	150
Total	250

Table 1. Contributions to the frequency error

The results in the table show that maximal frequency offset in the discussed case will be 250 Hz, which is one half of the frequency step during searching state. The detection of the presence of the EGNOS signal for designed receiver can be done by the search of the maximum of the correlation function for one frequency only, which is equal to L1. The task is thus simplified to a search in signal delay τ .

The other method that will speed up the algorithm of the search of the correlation function maximum is use of parallel computation of correlation function. The receiver in that case has to be able to compute during time interval T_C value of correlation function for all of investigated delays τ .

The signal processing algorithm of EGNOS signal detection implemented in the experimental GNSS receiver can be according the block scheme at Fig. 4 separated into four consecutive parts:

- Transformation of the intermediate frequency signal to the baseband and signal decimation
- Parallel computation of cross correlation function of received signal and its replica
- Noncoherent integration
- Search of the correlation function maximum and signal presence detection

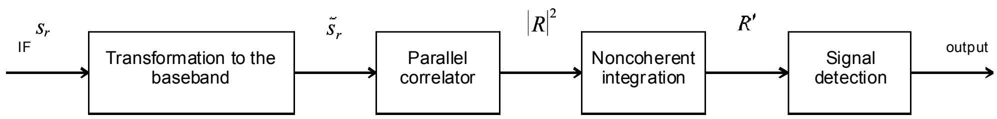


Fig. 4. Block scheme of signal processing algorithm

The whole signal processing algorithm was developed and tested in Matlab Simulink environment. Verified algorithms were then implemented to the experimental GNSS software receiver, developed at the Department of Radio Engineering of the Czech Technical University in Prague. The receiver design is based on FPGA device Xilinx Virtex-II Pro providing great flexibility together with sufficient computational performance for such operations. The implemented design provided reaction time to EGNOS signal presence better than 8 ms [5].

The equipment was installed in the common car. The measuring equipment has to measure and record presence of EGNOS signal and travelled distance. Because of complicated direct installation to the car the sensor of travelled distance was mounted to the carriage towed behind the car. The EGNOS signal was received by the common consumer GPS L1 antenna with magnetic mounting on the roof of the car. The measurements were realized during common traffic operations in typical environments: city of Prague, industrial town, village, highway, main and secondary roads in the country.

Figure 5 shows measured processes of EGNOS satellite shadowing in typical environments (village, main and secondary roads, industrial town).

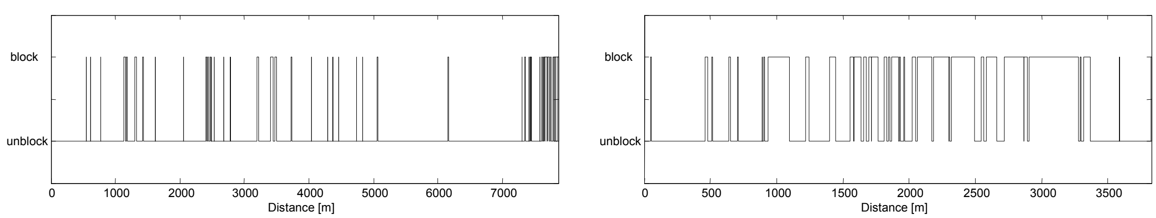
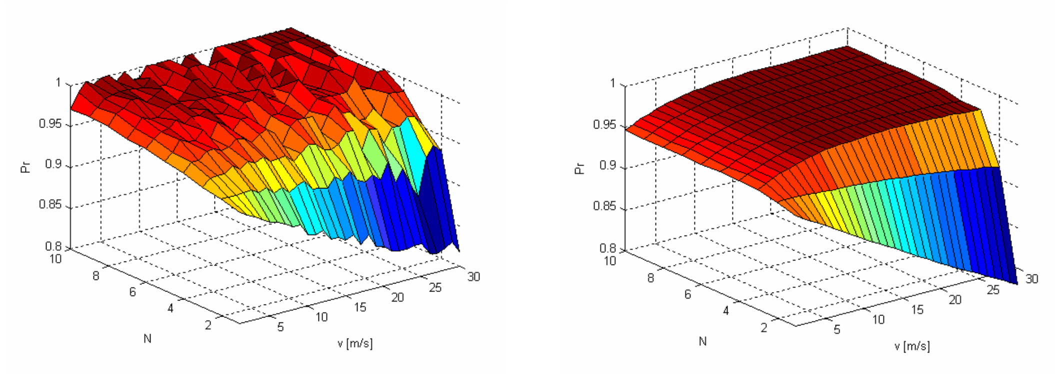


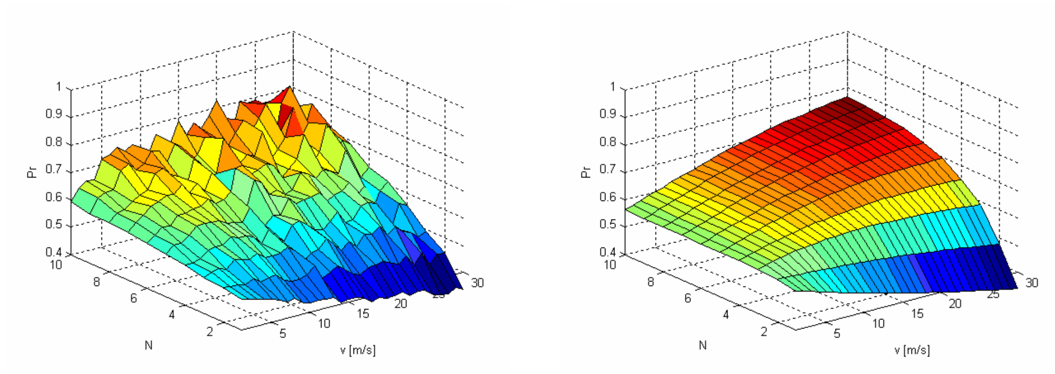
Fig. 5. The EGNOS satellite shadowing – village, main and secondary roads(left), industrial town(right)

After measurements, the probability of message reception was evaluated and compared to the results obtained by the use of theoretical model. Results of this analysis are shown at the Fig. 6 and Fig. 7.



(a) (b)

Fig. 6. The probability of reception of at least one message from N for real data (a) and mathematical model (b) – village, main and secondary roads



(a) (b)

Fig. 7. The probability of reception of at least one message from N for real data (a) and mathematical model (b) – industrial town

The experimental results have supported the conclusions we have got also from theoretical model that for some types of difficult environment the direct reception of augmented signals (SBAS, DGNSS) is not sufficient for ensuring the integrity and availability of the signal and GNSS performance thus can be negatively affected. That's why it is useful to support such systems by alternative dissemination of augmentation data.

DISTRIBUTION OF SUPPORTING DATA FOR GNSS

The dissemination of SBAS augmentation data can be realized by various means. However, the chosen method has to be available in the sufficient quality in locations where the difficulties with standard satellite signal reception fails. The microwave data links suffer from similar problems as satellite signals (visibility). A network of FM transmitters can be used for better coverage but it will not be wide enough to respect global nature of SBAS service, besides that the operational costs of continuous service would be very high. Similar solution is use of a network of DVB-T (terrestrial digital TV) transmitters that provide sufficient signal level for data reception. The DVB-T signal can be even used to providing another source of ranging signal [6].

Very prospective solution seems to be use of Internet for EGNOS data dissemination. The European Space Agency (ESA) supported these activities by realizing project SISNET (Signal in Space through Internet). The EGNOS data are distributed by TCP/IP connection to the users. Similar approach uses another network EUREF-IP, disseminating differential GNSS data from the several permanent stations of EUREF network.

The above described solution establishes common universal layer of data provision. The connection of the user to the Internet data can be solved according to the particular needs, i.e. it is available even for mobile applications. The classical solution of the "last mile" access is a use of cellular network with GPRS or UMTS capability. Such a connection can be established only in case of need, therefore it can save power of the device and operation costs for the user. Another advantage of the Internet use is in the fact, that it enables use of EGNOS data even for receivers that are not capable to receive and process EGNOS satellites signals, the data can be pre-processed and provided to the receiver in the standard RTCM format for differential corrections. Therefore the architecture of such a receiver consists from three main blocks, GNSS receiver itself, communication block for Internet connection, and data processing and control block that ensures augmentation data pre-processing for GNSS receiver, controls connection to the network in case of lack of EGNOS data from space (Fig. 8).

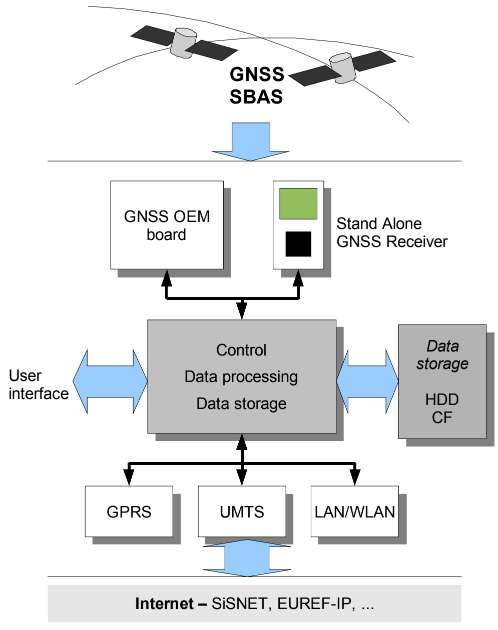


Fig. 8. Combined system architecture

We have verified the functionality of such combined system on reception of differential GPS corrections disseminated in EUREF-IP network [7]. The non-differential one-day stationary measurements were compared with measurements using RCTM based corrections from EUREF station GOPE in geodetic observatory Pecny. The results have shown improvement of position determination from 23.4 to 13.9 m RMS (Fig. 9) even for the environment suffering from signal obstructions and strong multipath. The corrections data GPRS based transmission latency did not exceed 2 seconds. The latency can however vary for places with lower GPRS coverage and will be object of further tests.

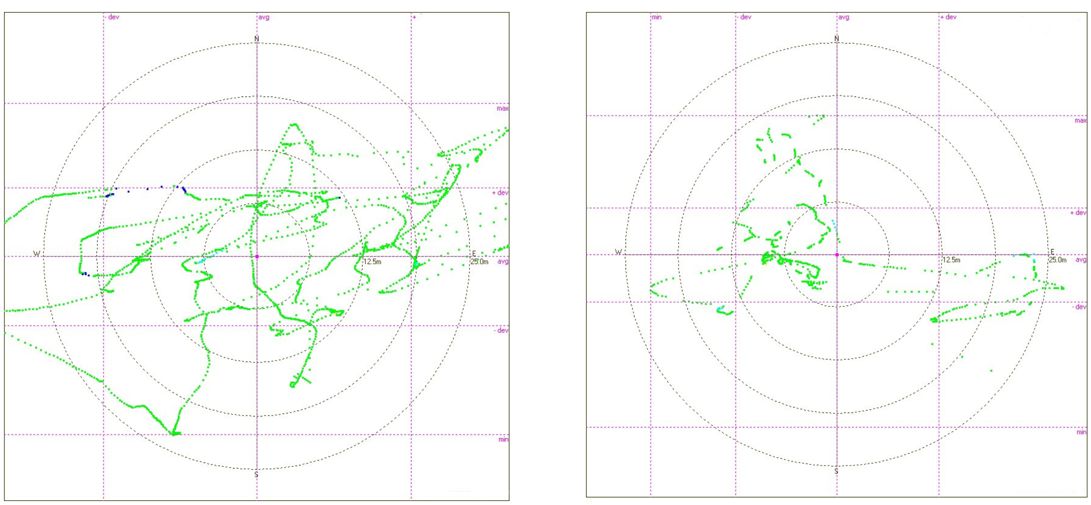


Fig. 9. Stationary GPS observations record and deviations for non-differential measurement (left) and with use of differential corrections from GOPE station distributed via Internet connection.

The possible evaluation of impact of alternative distribution of SBAS signal is complicated by the fact that conventional receivers are at present not able to process SBAS (WAAS, EGNOS) signals provided in other way than from direct reception via satellite. The signal has to be pre-processed to get corrections data in RTCM DGPS format which can then be loaded into classical receiver by external input (eg. RS232 serial link). However, the integrity information has still to be evaluated separately which leads again to combined solution described above. The solution can be the use of OEM GNSS module providing raw data measurements and final position and integrity computation would be executed in adjacent data processing block of combined design.

CONCLUSIONS

The GNSS performance use in difficult environment suffers from lower signal quality which can affect its performance in the meaning of the service precision, integrity or availability. Augmentation systems can be used to increase the performance but they are affected by difficult environment either. The SBAS signals are affected by shadowing in the line of sight which causes blockage of SBAS signal. The analysis of EGNOS signal availability was done for various types of environment. According to the measurements the channel model was designed and its use for computation of probability of EGNOS message reception was compared with results based on real measurements. Both analyses had shown that in some environments the availability of augmentation system satellite signals was not sufficient and some additional data transport should be used. According to this conclusion the combined system using Internet as other transport medium for augmentation data transfer. The functionality of such system was verified by tests with DGPS corrections received by GPRS service through EUREF-IP network. The future work shall cover use of SBAS data (e.g. SiSNet system data) for both precision and integrity enhancement in combination with raw data measurements.

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