On board localization technologies for vehicle positioning

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Abstract

This work is based on the results published by Hodoň, 2010a, where thorough analysis of all available localization techniques with their applicability to the vehicle positioning was performed. From the analysis made, the navigation by satellites was defined as the most suitable and promising technology for the purpose of the vehicle localization. Although, in last decades, the considerable improvements relative to the GNSS localization quality were introduced, provided accuracy is still insufficient for using in critical Safety-of-Life applications. Even the best and most expensive GNSS receivers cannot work flawlessly under specific conditions which are associated to the localization of the moving vehicle. If the GNSS systems are aimed to be used within the navigation system of the vehicle, deep analysis of the GNSS system performance and quality has to be performed. Currently, there is no approved and well-accepted procedure to determine the measurement quality of GNSS receivers. The novel method for the classification of GNSS receivers has been therefore introduced. The quality of any GNSS receiver can be described by the defined mainframe. The typical errors considered as the most worthy when navigating through GNSS as well as the size of error that is caused by them are described as well. Different augmentation methods as SBAS (Satellite-Based Augmentation Systems), A-GPS (Assisted GPS) or D-GPS (Differential GPS) are applied and examined among different scenarios. Methodology of Dead reckoning (DR) is presented within the special Inertial Navigation System (INS). The system is composed of a simple L1 C/A GNSS receiver taking advantage of SBAS - EGNOS and A-GPS CGEE upgrading. By application of Extended Kalman Filter (EKF), the minimization of position deviations measured by experimental INS vehicle can be observed. The developed system can be used as a universal platform for the dynamic localization accuracy testing.

Categories and Subject Descriptors

B.4.1 [**Input/output and data communications**]: Data Communications Devices; B.1.0 [**Control structures and microprogramming**]: General; B.8.1 [**Performance and reliability**]: Reliability, Testing, and Fault-Tolerance

Keywords

GNSS, vehicle, localization, navigation, inertial, SBAS, AGPS, RTK, DGPS, Kalman

1. Introduction

According to the definition in EEA Glossary, vehicle is any conveyance in or by which people or objects are transported. It is from Latin "vehiculum" which is an expression of transport, carriage or conveyance. It follows that the term "vehicle navigation" includes implementation of vehicle navigation methods in all kind of transport (road, railway, air, sea, etc.). Regarding an overview of the basic existing methods as well as related localization systems which was made by [18] (Table 1), the satellite navigation technology has been chosen for the purpose of this work.

Satellite navigation uses artificial earth satellites for the position determination [2]. It provides the global coverage and its usage is widespread - from the simple monitoring of vehicles up to the applications of the critical positioning operations. As described in [20], as well as in [48], the localization by GNSS is based on a precise timing of signals sent by GNSS satellites high above the Earth. According to a transit time duration of each signal, the distance of each satellite to the measured position on the ground is computed. GNSS receiver compares the time when the signal was sent by the satellite with the time when the signal was received and from this time difference the distance between receiver and satellite - range - is calculated. (1)

$$\rho_k = (t_r - t_{ek}) * c \quad (1)$$

World-wide GNSS systems can be classified, in general, into the two generation groups that cover four basic GNSS systems - GPS, Galileo, GLONASS and COMPASS.

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Table 1: Classification of available navigation techniques regarding the navigation method

Basic navigation methods	**Complex navigation system**
Dead reckoning	Radio navigation
Pilotage	Radar navigation
Celestial navigation	Satellite navigation

Though GPS and GLONASS are practically exploitable, Galileo and COMPASS are under the various state of development. More info about mentioned systems can be found in [18], regarding publications of [30], [38] or [3] as well as web-pages of the single systems operators (IAC, ESA, NASA,...). By combination of the existing satellite navigation systems (GPS and GLONASS), with Satellite Based Augmentation Systems (SBAS) or Ground Based Augmentation Systems (GBAS) the first generation systems can be depicted - GNSS-1. The second generation system - GNSS-2 provides the accuracy and integrity that is necessary for civil navigation (Galileo, GPS III). It consists of L1 and L2 frequencies for civil use and L5 for system integrity.

2. GNSS Localization Error Sources

As the GNSS (or another radio) signals propagate from the Earth Orbit satellite through the atmosphere to the appropriate receiver, on the ground, they are refracted in various ways. Generally said, regarding [20] as well as [19], accuracy of any GNSS system could be as an accuracy of every common measurement system affected by two kinds of errors - systematic errors e_s and random errors e_r. Observed value X is then summation of true value T and accumulated error e divided into two subcomponents e_r and e_s. (2)

$$X = T + \underset{e_r+e_s}{E} \quad (2)$$

Systematic errors distort measurement results always in one way as a bias with tend to be consistently either positive or negative. They are caused by any factors that systematically affect measurement of the variable across the sample. The random error is the fluctuating part of the overall error that varies from measurement to measurement whereas it is defined as the deviation of the total error from its mean value.

When considering measurements in 2D as *f(x, y)*, where x represents determined Latitude and y Longitude, the range of estimated position results as the function of time *f(t)* affected by an absolute error $\varepsilon(\tilde{e}) \geq |e - \tilde{e}|$, where $\tilde{e}$ is an approximation of the measurement random error e, could be described as $< \varepsilon(\tilde{e}) - \delta; \varepsilon(\tilde{e}) - \delta >$, where δ represent the contribution of systematic error. This could be in general characterized as the circle function *k(S[x,y];δ)* (Figure 1)[22].

With regards to the previous definition, the difference between random and systematic error that can occur during GNSS localization process and can affect its localization accuracy can be described as in [18].

Regarding [18] as well as the paper [19], following errors are considered as the most worthy when navigating through GNSS:

- Geometry of the satellite constellation and satellite

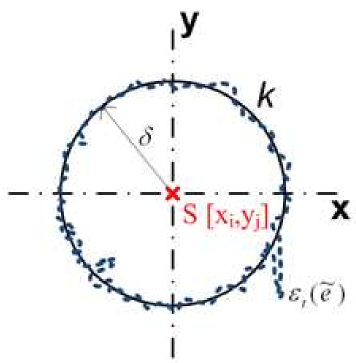

Figure 1: Circle interpretation of the static 2D localization function.

shading - Geometrical alignment of the satellites can be described as the position of the satellites to each other from the view of the receiver. To indicate the quality of the satellite geometry, the DOP values (dilution of precision) are commonly used:

  – GDOP (Geometric Dilution of Precision) - overall-accuracy; 3D-coordinates and time.
  – PDOP (Positional Dilution of Precision) - position accuracy; 3D-coordinates.
  – HDOP (Horizontal Dilution of Precision) - horizontal accuracy; 2D-coordinates.
  – VDOP (Vertical Dilution of Precision) - vertical accuracy; height.
  – TDOP (Time Dilution of Precision) - time accuracy; time.

The error caused by bad satellite geometry does not cause inaccuracies in the estimated position accuracy that can be measured in meters but it can amplify other inaccuracies, such the multipath, that are then quite high. In general could be this error described as (3).

$$f.s(t + \delta_t) \quad (3)$$

- Multipath effect - Multipath is the event when the GNSS signal arrives at a receiver's antenna via more than one different paths whereas it affects both pseudorange and carrier phase measurements. In GNSS static and kinematic precise positioning, the multipath effect is an error source that has to be taken into account [48]. Regarding [48] as well as [19], it has to be also mentioned that multipath is a very localized effect, which depends only on the local environment surrounding the antenna. Considering the direct signals $s(t) = Acos(\omega t + \phi)$, where textitA is the amplitude, ω is the angular velocity and φ is the phase; then the indirect signal can be represented as (4).

$$E_p = E_r * DOP \quad (4)$$

- Atmospheric effect - Atmospheric effect is phenomenon whereby is GNSS signal degraded when passing layers of the Earth's Atmosphere. It is caused by the different densities of Ionosphere and Troposphere, which slow down the signal speed and therefore cause the signal delay. Influence of atmospheric effect can

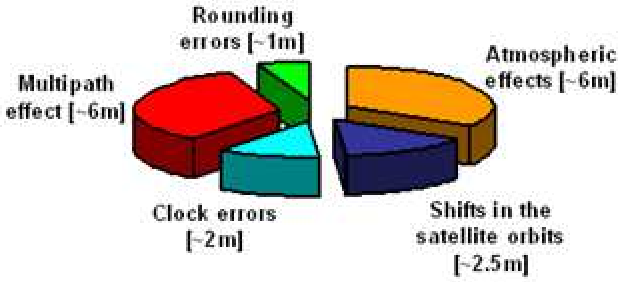

Figure 2: Graphical interpretation of the GNSS error sources and the size of error that they cause.

Table 2: GNSS error sources and the size of error that they cause

Type of Error	Error Size
Atmospheric effects	± 6.0 m
Shifts in the satellite orbits	± 2.5 m
Clock errors	± 2.0 m
Multipath effect	± 6.0 m
Rounding errors	± 1.0 m

vary, but in peaks it can cause localization inaccuracies for about ±6m [19]. The change of the length of the signal transmitting path in the medium with refractivity textitn is shown in [48]. Atmospheric effect strongly depends on the local environment surrounding of GNSS receiver.

Incidence of the other systematic errors, such Orbital error, Receiver clock error and Error caused by relativistic effects is very infrequent since these errors are caused either by computing errors in control segment of the system or by the defects in hardware or software of the single receivers and the prevention of all these complications is secured very well by the single chip producers or by the system operators keeping the system integrity on very high level.

Regarding [16]; [17] and [22], in the Table 2 as well as in the Figure 2, there are summarized all error sources with the information about the size of errors that can be caused by them. Resulting error of ca. ± 17.5 meters provides sufficient information about the GNSS localization accuracy.

3. Introduction of a novel method for the Classification of GNSS receivers

If the GNSS systems are aimed to be used within the navigation system of the vehicle, deep analysis of the GNSS system performance and quality has to be performed. As regarding the basic model of GNSS quality described by [14] as well as [46], the quality of a GNSS-base vehicle system can be described by four main features - Accuracy, Availability, Reliability and Integrity (Figure 3). From the general point of view, by including the Availability into the Reliability item, since the system availability is a part of system reliability, as well as by the splitting the Accuracy into the Accuracy and Precision items, the quality of whole GNSS system can be described according to the schematic provided by the Figure 4 [22].

Figure 3: GNSS quality.

If the quality of vehicle navigation is going to be described, the quality at the User-Side plays the most important role since the quality of the system side is controlled by the system operators and is for all vehicles constant in time. The User-Side of GNSS system is represented by the system users, which are in general the GNSS receivers. Therefore Accuracy and Precision items can be generally considered as the main characteristics describing quality of any GNSS receiver. However, since the quality of GNSS receivers is more complex than to be described only by two features, regarding [22], as well as application notes from [42]; [43] and [1]; as well as considering the basic parameters of every GNSS receiver; the five key tests that together determine performance of any GNSS receiver has been defined as following:

- Acquisition and tracking sensitivity;
- Time to first fix and reacquisition time;
- Static navigation accuracy;
- Dynamic navigation accuracy.

These four features should be considered when the quality of the User-Side of GNSS system is examined. This means that the quality of any GNSS receiver can be described by these four characteristics. Beside these, the receiver's functionality specifications could represent another parameter that should be considered upon the receiver's quality investigation. This is, however, very specific parameter applied differently under various specific conditions. It comprises, for example External Antenna Option, Rugged and/or Water-Resistant Construction, Bluetooth and/or GSM Modem Presence, Batteries Capacity, Ability to Average Positions into a Point, etc.. Hierarchic description of the GNSS system User-Side Attributes is provided in the Figure 4.

3.1 Acquisition and tracking sensitivity

Acquisition and tracking sensitivity of GNSS receivers could be generally characterized by four basic features:

Receive sensitivity - Receive sensitivity [dBm] is in general one of the key specifications of any radio. It indicates how faint an RF signal can be to be successfully received and processed by the receiver. The

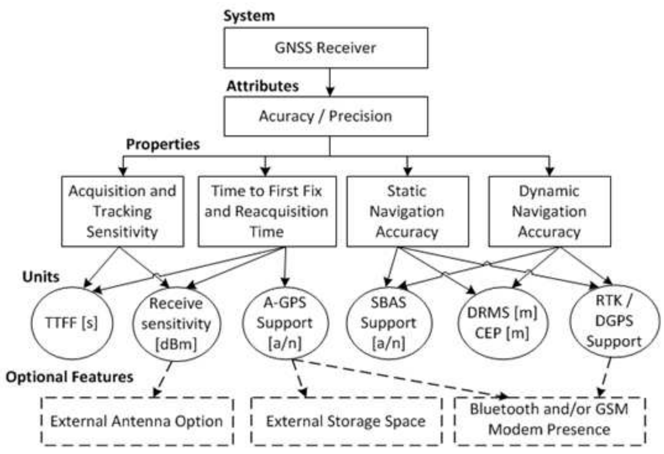

Figure 4: Hierarchic description of the GNSS User-Side attributes.

lower the power level that the receiver can successfully process, the more sensitive the GNSS receiver is. Considering [42], the tracking sensitivity of the receiver represents the minimal signal power level at which a GPS receiver will keep the tracking loops closed, though the acquisition sensitivity represents the minimum signal power level at which a GPS receiver can autonomously acquire satellites and calculate a navigation solution. Generally said, the limiting factor is the receiver's ability to decode the Navigation Message from the satellite signal. Even if the receiver can track a signal, it cannot form a position without ephemeris data from the Navigation Message. Acquisition sensitivity of the GNSS receiver can be then summarized into the two main conditions:

- ephemeris available from any source,
- ephemeris must be obtained from the satellite data stream.

For conditions where ephemeris is available, the minimum signal level that reaches the Earth is -130dBm. When an ephemeris has to be decoded, the signal must be much stronger, the limit is -147 dBm in the latest release of Sirf III specification. In order to recover the navigation signal successfully, active antennas are typically utilized with gains of 20 or 30 dB [7].

Jamming Resistance - Regarding [36], RF interference (RFI) has been and will continue to be a significant worry for GNSS users. It can be split into the three main categories:

- The first category is malicious interference,
- The second category is uninformed interference,
- The third category is accidental interference.

The special external antennas, such as for example Novatel Gajt Q4 2011, are used to circumvent this problem. As regarding [15], it is obvious, that integration of RF filters together with Low Noise Amplifiers is assumed for the RF noise minimization.

When considering signal and noise paths through the front-end, one needs to consider the noise figure (NF) of the various components in the front-end [34]. The Carrier-to-Noise Density (C/N0) in [dB-Hz] as well as Signal-to-Noise Ratio (SNR) in [dBm] or in [dBW] can be used for describing the strength of the signals which are the receivers able to track. Regarding [35]; as well as [27]; bit error rate testing (BER tesing) is a powerful methodology for end to end testing of digital transmission systems, since it provides a measurable and useful indication of the system performance that can be related to its operational performance. The confidence level (CL) is the percentage of tests that the system's true BER is less than the specified BER. C/N0, SNR and BER are important quantities when designing, evaluating and verifying the performance of any GNSS receiver. Furthermore, regarding [15] as well as [40], parameters of implemented LNA as Gain, Noise Figure and 1 dB Compression Point should be also considered.

Position Update Rate - Every GNSS receiver sends out the positioning output data within some certain rate. In general is this rate measured in Hz and in common receivers is this rate located in 1 - 50 Hz interval. In general as in every measurement system, the more measurements are made, the more likely will their average value approximate the true value. Regarding [44], the "quality" of the data set with data points that are less scattered is greater, since the precision of the result is better. The quantitative measure of this precision is given by the standard deviation. Therefore, as higher is the positioning and heading output update rate of GNSS receiver, as better position info is provided to the final customer. Improved positioning rate enhances positioning stability, especially in urban areas, by reducing the position errors around high buildings and under elevated structures.

Satellites Segregation - Number of parallel satellite-tracking channels defines the number representing an amount of channels processed by the receiver simultaneously. The receiver has dedicated separate hardware to receive each satellite that it needs for a solution. Parallel receivers provide faster signal acquisition and reacquisition as the sequential or multiplexing ones that are rather capable of tracking the great amount of satellites but not simultaneously. In order to obtain a good navigation solution, it is necessary to operate enough tracking channels in a GNSS receiver to obtain sufficient satellites in view to achieve good geometric dilution of precision. Position accuracy depends generally on two things: the orientation of the GNSS satellites at a given time and the accuracy of the GNSS signals themselves. Regarding [8], the metric defining the orientation of the satellites is Dilution of Precision (DOP), the metric defining the accuracy of the satellite signals is User Range Error (URE). As regarding [49], the satellite-receiver geometry changes with time due to the relative motion of the orbiting satellites and the different satellite-receiver geometries can amplify or reduce the errors in the positions derived by GNSS. According to [49], positioning accuracy can be then estimated as the ranging accuracy multiplied by a dilution factor that depends solely on the satellite-receiver geometry. The conventional GNSS satellite selection algorithms are then executed using the combinations of satellites with the highest elevation angles selecting the combination with the smallest

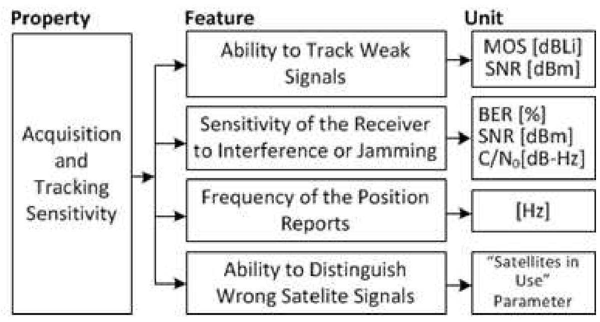

Figure 5: Acquisition and Tracking Sensitivity Features of GNSS receivers.

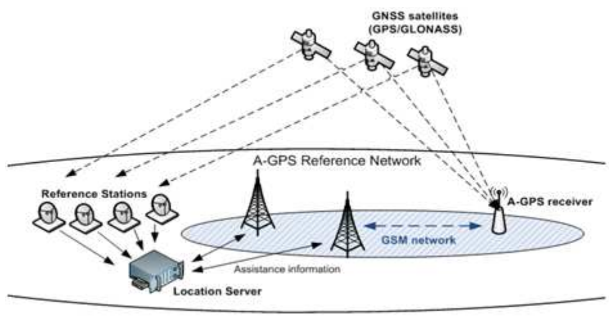

Figure 6: A-GPS system infrastructure.

GDOP. Though the new satellite constellation slot definition allows optimization of satellite orbital positions, fewer satellites oriented optimally are better than more satellites oriented sub-optimally. From the measurement taken in [8], it is evident that the more satellites are available, the better DOP values are derived but it does not automatically mean that the accuracy will be higher since some areas of relatively high PDOP (4-5) had very low navigation error, conversely, some low PDOP data points had a comparatively high navigation error, meaning the pseudorange errors are large at those points.

Regarding [31], even where the highest possible number of satellites is used by the receiver, multipath effect is still a major limiting factor in achieving high accuracy solutions. In [31], various methods for mitigating the effect of multipath interference on code phase and carrier phase measurements have been summarized allowing receivers to resolve position off-sets by using satellites which have little or no errors caused by multipath:

- Antenna-Based Techniques;
- Signal-Processing Techniques;
- Measurement-Processing Techniques.

Regarding mentioned, the presence of algorithms that can allow GNSS receiver to distinguish between the textitSattelites_in_View and *Satellites_in_Use* attributes is crucial for its quality investigation. The performance of any GNSS receiver is then characterized by the *Number_of_Tracking_Channels (NTC)* as well as by the *Number_of_Acquisition_Channels (NAC)* parameters, where the higher values represents the higher quality of GNSS receiver, while at the same time $NTC < NAC$.

In the Figure 5, there are summarized all features regarding the Acquisition and Tracking Sensitivity property of GNSS receivers.

3.2 Time-To-First-Fix

Time-To-First-Fix [s] (TTFF), as one of GNSS receiver quality interpreting attributes, represents the time necessary for the acquisition of satellite signal and navigation data to compute the position solution (fix). In general it recognizes three states - Hot Start (HS), when receiver contains valid almanac and ephemeris data, Warm Start (WS), when receiver contains valid almanac data but no ephemeris and Cold Start (CS), when receiver doesn't contain neither almanac nor ephemeris data, while $t_{HS} < t_{WS} < t_{CS}$ [22]. TTFF parameter is important mainly in dynamic navigation situations, where just the short signal lost results to the inaccuracies of about hundreds meters, so the time of signal reacquisition is therefore quite critical. Since the vehicle is moving, it obviously crosses areas with various surrounding conditions and its positioning algorithms have to be coped with any kind of situation. Satellite shading or signal lost are states which occurrence is very frequent. The signal reacquisition time is therefore one of crucial parameters for localization quality describing. Various methods could be applicable for the TTFF shorten, due to the availability and manufacturers support, the technology of Assisted GPS has to be considered for this purpose [24].

Assisted GPS (A-GPS) is an enhancement position location method applied to the GNSSs since it is based on the additional positioning info to the localization process comprising. This additional information is called Assistance Data and allows the receiver to determine and report its exact location within seconds as opposite to minutes when using unassisted GNSS techniques. It employs data connection to reduce the time required by GNSS (GPS/EGNOS/GLONASS/...) enabled device to find its current position (TTFF). GNSS receiver normally requires at least 18-36 seconds in order to obtain the orbital data and calculate the first position while under difficult reception conditions (e.g., in urban areas where tall buildings block direct sight to the sky) the calculation of the first position can require minutes to be completed [45]. In the absence of the orbital data, the GNSS receiver must carry out a complete search procedure in order to find the available satellites, download the data and calculate the position, what is very time demanding [45]. This time delay is a system-inherent limitation of GNSS, which could be crucial when the fast moving vehicle is locating. Various aided data integrated into the GNSS localization process via additional communication link should be therefore considered. In general, A-GPS system consists of a network of reference stations that are constantly monitoring GNSS satellites, a central location server which distributes assistance information, and A-GPS capable receivers (Figure 6). To integrate A-GPS, an integration of interface through which can be the Aiding-Data received is required at the receiver's side. Typically, UART, USB, or CAN interfaces are employed when connecting with special data modem, most GPRS module . In practice, A-GPS is used for overcoming uncertainties associated with signal acquisition in low signal and degraded signal environments such as tunnels, buildings, tree alleys, etc. It enhances the receiver's ability to track

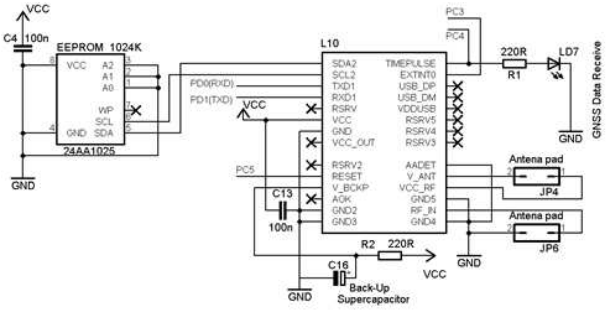

Figure 7: Simplified schematic of CGEE A-GPS system based on ATMega8.

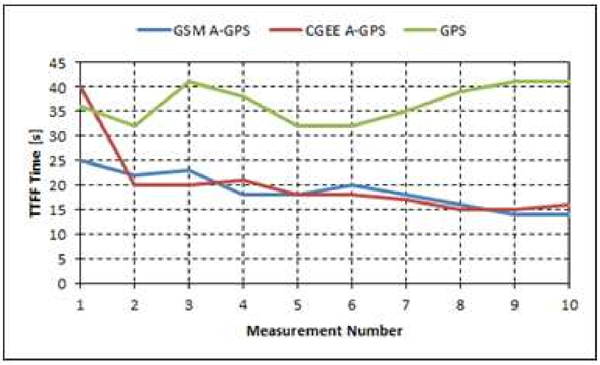

Figure 8: Comparison of acquisition times between GSM A-GPS, CGEE A-GPS and common GPS receiver in the measurement taken in 20th November 2012.

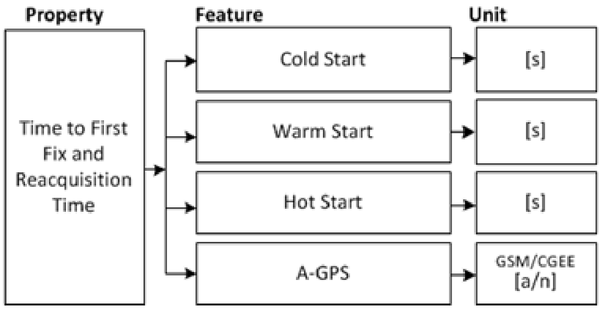

Figure 9: TTFF and Reacquisition Time Features of GNSS receivers.

low-power GNSS signals and speed up reacquisition time during the signal lost. Disadvantage of typical A-GPS is the costs increase - an access to A-GPS reference network as well as the data transmission via GSM/GPRS network is obviously charged. Except the traditional A-GPS, an existence of A-GPS with offline aiding data utilization is obvious as well. This concept reckon with employment of external memory, where Client-Generated Extended Ephemeris (CGEE) data are stored. By utilization of this method, ephemeris over at least three days can be autonomously predicted without any server assistance. With SiRF CGEE technology CGEE-start time of less than 15 seconds under most conditions can be delivered without any network assistance. Many of presently available chips provide A-GPS CGEE support stardandly. L20 Quectel GPS Engine was chosen as an example for CGEE implementation. The external 1Mbit EEPROM is used to store CGEE data generated by SiRF starIV chip through I2C port. The I2C port is open drain output and supports up to 400kbps for accessing the EEPROM, the data line and clock line are internally pulled up to power supply by 2.2K resistors. When implementing - accessing EEPROM to store EE data, NMEA protocol mode has to be switched to OSP protocol mode and input defined message "A0 A2 00 03 E8 FD 01 01 E6 B0 B3" has to be send as the Receiver-Command-Input. To acquire the data from EEPROM back the command "A0 A2 00 0A B2 03 02 04 80 04 25 28 02 5C 01 EA B0 B3" has to be insert. After finishing the CGEE will be achieved. This methodology is aplicable even in the real-time positioning because all operations mentioned last at the baud rate of 115200 bps only 70 ms [37]. By employment of CGEE together with an external GNSS antenna installed at the position with the clear skyview, the times of GNSS navigated vehicles required for becoming operational could be shorten considerably.

For A-GPS performance investigating, the experimental measurements has been performed measuring TTFF of traditional GSM based receiver integrated within the common Android smartphone Samsung GT-S6500 Galaxy Mini 2 comparing to the CGEE supporting GNSS receiver Quectel L20 implemented together with ATMega8 and 1024kB EEPROM as shown in the Figure 7. Both devices was being periodically turned on, until the valid GNSS signal has been captured. The signal LED diode in CGEE A-GPS device informed about valid data reception, in the mean time smartphone OS informed about valid data reception by the information message. The time of signal acquisition was recorded and the devices were then turned off. After the 5 minutes break was then situation repeated until the 10 measurements were taken. Mesured results were then compared with data recorded by normal receiver without A-GPS support (Holux M1000-C). From the measurement is obvious that both A-GPS techniques improve the TTFF times by almost the same way. Comparing to the common receiver, without A-GPS support, circa 50% shorten of the TTFF cold start time could be observed. From the results is evident, that support of A-GPS technology is one of the key parameters of GNSS receivers when TTFF performance is considered. Graphical representation of the results is shown in the Figure 8. In the Figure 9, there are summarized all features related to the TTFF and Reacquisition Time properties of GNSS receivers.

3.3 Static Navigation Accuracy

Static Navigation Accuracy of GNSS receivers could be in general characterized by three basic features:

- Producers' parameters;
- SBAS support;
- DGPS Support.

When describing the quality of GNSS receiver's Static Navigation Accuracy, the distinction between the accuracy and precision should be defined and considered. Accuracy is the degree of closeness of an estimate to its true, but unknown value and the precision is the degree of closeness of observations to their means [32]. Accuracy indicates proximity of measurement results to match the true value, precision the ability of measurement to be consistently reproduced. By comparison of the accuracy and precision parameters of the GNSS receivers, the receivers' performance classification can be introduced as regarding [22]. Annular comparison can be used to explain difference between these two terms.

Theorem 1. *Let two circle functions $k(S[x_i, y_j]; \delta)$ and $k'(S'[x'_i, y'_j];$ with $\delta'), \delta' \subseteq \delta$, first representing whole range of values (k), second the specific situation (k') of GNSS receiver will be defined. Following cases related to the position estimating could arise:*

A) HAHP - High Accuracy, High Precision, when $S \approx S' \wedge \delta \gg \delta'$,

B) LAHP - Low Accuracy, High Precision, when $S \neq S' \wedge \delta \gg \delta'$,

C) HALP - High Accuracy, Low Precision, when $S \approx S' \wedge \delta \geq \delta'$,

D) LALP - High Accuracy, Low Precision, when $S \neq S' \wedge \delta \geq \delta'$.

These states could be in practical realization described by scatter plots, which can be provided either by GNSS chips' manufacturers or measured in practical experiments. Scatter plot is defined as the dispersion of estimated positions logged over specified time period scattered due to measurement errors over an area which is called confidence region. Confidence region is analyzed to quantify the GNSS performance statistically. The confidence region with a characteristic radius describes the probability that the solution will be traced within the specified accuracy. Manufacturers represent this (in 2D positioning) by two features supplied together with receivers' documentation:

- Distance Root Mean Square (DRMS) - The square root of the average of the squared horizontal/vertical position errors (HRMS/VRMS),
- Circular Error Probability (CEP) - The radius of circle centered at the true position, containing the position estimate with probability of 50%.

For the investigation of the weight of these parameters in the frame of the GNSS receiver localization accuracy and precision, 27 hours remained experimental measurement of static localization accuracy was realized in the period of 13.-14.7.2010 in Žilina [20]. As a reference was used the ETRS89 (The European Terrestrial Reference System 1989) geodetic point 2631ZA-1006 located on the top of the hill, above the all housing developments, without any barriers that could block clear view on the sky. The inaccuracies occurred during measurement can be seen in the Figure 10, where the scatter plot of measured values is depicted. When the analysis of measured results was performed, first five positions measured were disregarded due to the TTFF considerations defined by the receiver's chip manufacturer [6] since the deviations brought along the first measured points were quite high. This was caused by the wrong algorithms implemented within the GNSS receiver regarding the *"Satellites_in_Use"* parameter. Regarding [14], Mahalonobis Distance Algorithm

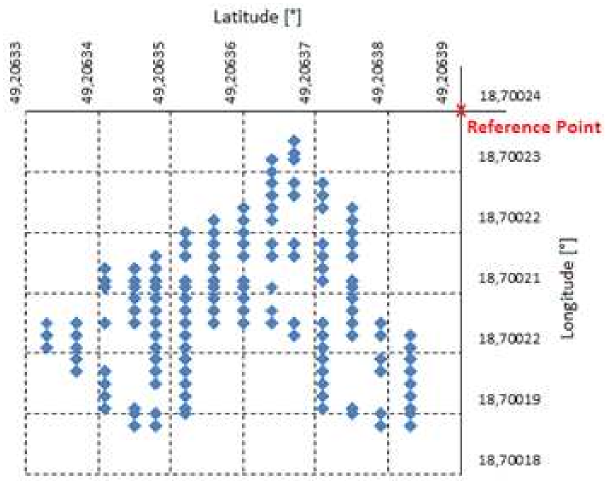

Figure 10: Scatter plot of measured positions.

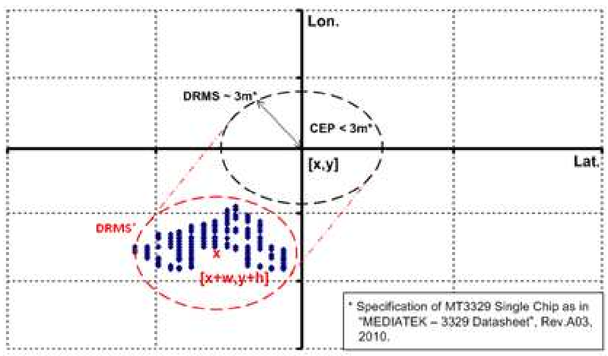

Figure 11: Scatter plot of measured positions.

can be used for identifying different patterns within related datasets, by analyzing the similarity of unknown samples from one dataset to a known one since it takes into account the correlations of the entire dataset. From the measurement is also obvious that DRMS and CEP parameters defined in specification of utilized GNSS receiver chip ($DRMS_{spec.} \sim 3m; CEP_{spec.} < 3m$) [6] did not report the receiver's quality properly. Although investigated dispersion of estimated positions was even better than referenced values ($DRMS_{inv.} \sim 1.8m; CEP_{inv.} \sim 1.5m$) determined position were shifted ($Modus\_Value \sim 6.7m; Mean\_Value \sim 6.2m$) according to the real position of the reference point where the measurement was taken. What is important is that this shift is much higher than defined DRMS radius, so the position values are out of range. The shift is shown in the Figure 11 and it could be represented as $DRMS(S[x, y]) \rightarrow DRMS'[x + w, y + h]$, where w, h comprise uncertainty due to the systematic error.

Regarding [50] and [16], as well as previous measurement, the latency of signal arrival caused by the effect of atmosphere can cause inaccuracies that can be measured in meters. This effect occurs when the satellite signal passes through the Earth's layers Troposphere and Ionosphere, where it is delayed. This time delay may cause errors in calculating of the exact time and position. Satellite-based Augmentation Systems (SBAS) have been therefore introduced to minimize an influence of this effect. With the implementation of SBAS, it is possible to set up "maps" of the atmospheric conditions over different regions. By sending of the data corrections to the receivers, the quality of the localization process can be enhanced considerably. SBAS provide simple, inexpensive and powerful means for suppressing consequences of this effect. SBAS is in essence a kind of DGPS (Differential GPS) with such no limitation in correction broadcasting. It uses a multiple network of fixed, ground-based reference stations to broadcast the differences between the positions indicated by the satellite systems and the known fixed positions to increase the positioning accuracy. It consists of the space segment which is made of the satellites and of the ground segment which is made of the network of reference stations so it can cover and operate over quite large area. Ground stations transmit Atmospheric corrections and integrity information through geosynchronous communications satellites directly to the user, so it supports wide-area augmentation through the use of additional satellite-broadcast messages. As regarding [29], the most important feature of the SBAS systems for common GNSS users are the Ionospheric corrections served as the IONO correction grid that is purveyed by the single SBAS. This grid is computed from the data measured in Ionosphere as a "map" of Total Electron Content (TEC) and it provides information about conditions within this layer [17]. There are several SBAS systems available over the world with various degree of coverage, including from the 1.10.2009 also the European Geostationary Navigation Overlay Service (EGNOS). EGNOS consists of the transponders system, placed on the three geostationary satellites; from the network of circa 40 ground stations (Ranging and Integrity Monitoring Stations - RIMS); from the four master control centers (Gatwick (Great Britain), Langen (Germany), Torrejon (Spain) and Fucino (Italy)) and from the six up-link stations [10]. The Open Service of EGNOS is provided free of charge, so all of the GNSS chips with integrated EGNOS support should provide better localization accuracy after the initiation of this service.

For investigation of the GNSS accuracy together with the open EGNOS Service application was chosen the chip MediaTek MT3329 implemented in Holux M-1000C GPS receiver. It was the same receiver as used in the TTFF measurements. MT3329 integrates, for achieving the best GPS receiving performance, a CMOS RF down-conversion circuitry, a base-band signal processing engine and it can track up to 66 satellites. It also provides a very good sensitivity on a receiving satellite signal, up to -165dBm. Embedded WAAS/EGNOS demodulator, which is by default disabled, allows using DGPS - SBAS mode without any additional hardware. With orbit satellites it communicates through C/A code (Coarse/Acquisition code) on a single frequency (L1 = 1575.42MHz) and with control devices through the protocol NMEA 0183 (V3.01). Measure method was based on an adequate amount of position measures made on the known static reference point, and on the differences between sizes of the errors acquired during the measurements with EGNOS support enabled and disabled analysis. Measurement was taken on 23rd February 2010 in a time period from 09:00 AM to 12:00 AM. During this time it was stable weather, +7 °C, half-cloudy (circa 25% cloud amount), atmospheric pressure 100kPa and no precipitation (measured by Slovak Hydrometeorological Institute). GNSS receiver was fixed on a reference point position, which was clearly determined due to the unequivocal geodetic sign. Then it started to perform localization process in that way, that first 2 hours

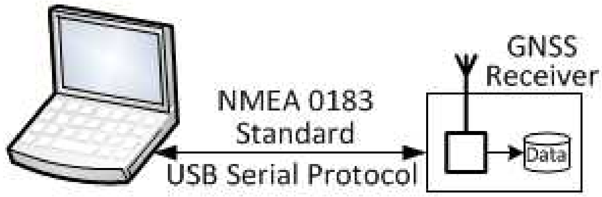

Figure 12: Control of GNSS receiver through NMEA 0183 via USB.

Table 3: The structure of applied commands for turning the EGNOS on

$PMTK301, mode	**$PMTK001, cmd, flag**
301 - PMTK_API_Set_Dgps_Mode (GPS correction data source mode)	001 - PMTK_ ACK (Acknowledge of PMTK command)
N/A	cmd - The command (packed) type acknowledge respond
mode (DGPS data source mode): 0,1,2	flag (DGPS data source mode):0,1,2,3

was the SBAS mode disabled and next 2 hours was the SBAS mode enabled. Since the receiver was connected via USB interface to the laptop computer too, the position measures could be stored beside its own memory also in that, provided by the computer. Moreover, the control of GNSS receiver functioning was performed via USB interface as well. The NMEA 0183 communication standard was used for this purpose (Figure 12).

Within the measurement, GPGGA NMEA 0183 message was used for the recorded data analysis, since it comprises info about measured latitude and longitude separately. At GPGGA frequency of 1Hz circa 14400 measurements were performed, for each case 7200. For turning WAAS/EGNOS support on, NMEA 0183 input command for MTK chips *"$PMTK301,2"* was sent via serial protocol, correctness of an executed task was confirmed by the response *"$PMTK001,301,3"*. Structure of the used commands is shown in the Table 3.

After the measurement finishing followed by the analysis of all measured data from the device log, an impact of the EGNOS support on the accuracy of GNSS localization can be seen in the Figure 13. From the pictures is evident that, by applying of the EGNOS service was the quality of GNSS localization increased since the systematic error occurred within the first measurement was minimized, though not fully surpressed. This improvement can be seen on the differences between arithmetic means and variances computed from the single data acquired during the measurements (Table 4 and Table 5).

During localization with EGNOS support it must be considered that reading of the information from EGNOS satellites takes obviously several minutes, data has no long lifetime period and the battery usage is higher. Its correct operations are also conditioned by the clear view on the geostationary satellites, in our case a clear view on the South was crucial, and simultaneously the minimum of 4 GNSS satellites have to be tracked. If it is visible less than 5 GNSS satellites (1 EGNOS + 4 GNSS), GNSS

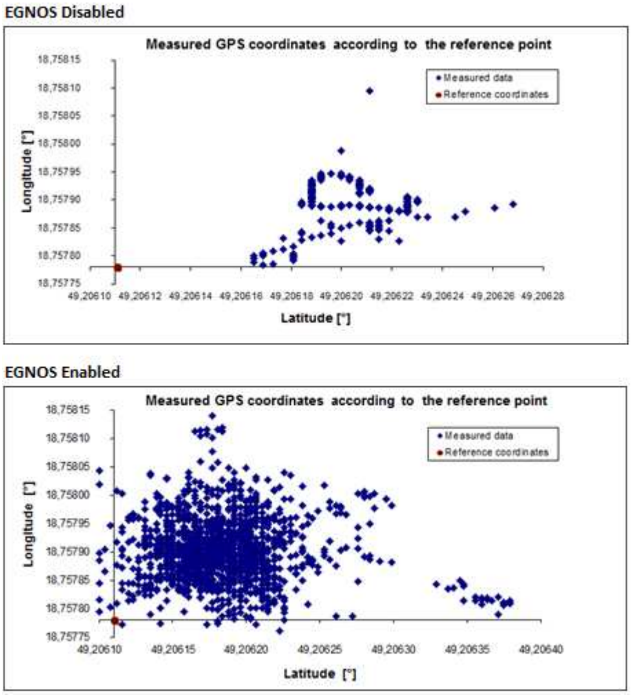

Figure 13: Measured coordinates with EGNOS support disabled/enabled.

Table 4: Expected values of coordinates confronted with reference coordinates.

	Latitude	Longiitude
Reference point	49°12′22.000”	18°45′28.0000”
EGNOS disabled	49°12′22.1796”	18°45′28.1484”
EGNOS enabled	49°12′22.0896”	18°45′28.0944”

receiver has not enough information for the SBAS corrections application. In spite of this, using of EGNOS service provides considerable improvement of the localization quality.

Differential GPS (DGPS) is another method that can be applicable as the GNSS localization enhancement technique. The underlying premise of this technique is that any two receivers that are relatively close together will experience similar atmospheric errors. It uses a multiple network of fixed, ground-based reference stations to broadcast the differences between the positions indicated by the satellite systems and the known fixed positions to increase the localization accuracy. It involves the cooperation of minimally two receivers; one that is stationary - base station, and another that is performing the measurements - rover [18]. The stationary receiver must contain the precisely determined coordinates because it is functioning as a key. It collects data from all visible satellites and compares them with predicted satellite ranges. The difference is the satellite range error, which is then converted to correction signals for use by a roving receiver. This correction may be done real-time or afterward as the Post Processing DGPS and it can improve localization accuracy up to cm level. DGPS requires raw data measured from separate receivers to be combined into a single range difference. For Real Time Kinematic (RTK) data collection, the raw data can be broadcasted using a radio link or cell phones and the differential solution is solved in real time. RTK is a technique used especially in a land survey based on the use of carrier phase measurements of the GNSS signals where a single reference station provides the real-time corrections. By this method an existence of an amount of reference stations where correction data are computed is assumed. Correction values or corrected observations are then transmitted to the user side presented by GNSS receiver by using a suitable medium, mostly the mobile communication networks (GSM/GPRS) in bands (450), 900 and 1800 MHz according to the RTCM SC 104 standards. Compensation for the determined pseudoranges to correct the calculated position is performed at the user side where an existence of additional hardware, mostly UHF or GSM/GPRS modem, is assumed. According to the implemented communication standard, an access either to the single or to the multiple reference RTK stations could be envisaged. Multiple reference RTK stations are considered as a natural extension of just the pure single reference station application. Although there may exist cases when solution provided by single reference station is better than the network solution. The network solution is generally more likely to accurately represent the errors over the region because of the additional information gained from combining the data from all reference stations [33].

Table 5: Improvement of the total variance influenced by EGNOS service.

Receiver State	Variance
EGNOS disabled	2.41476 E-08”
EGNOS enabled	0.10484 E-08”
Improvement	**2.30992 E-08”**

One of the key parameters of the DGPS-RTK technique is an ability of the receiver to connect to the appropriate RTK network and get the fixed solution - RTK initialization time. Since only when the DGPS solution is marked as a fixed in time, only then is the derived RMS guaranteed by the service provider. However, in real scenarios very often happens that communication among receiver and RTK network is somehow disturbed or even cancelled. Reconnection and initialization times are therefore very important when the GNSS system performance with respect to the requirements of designated application is quantified. Therefore, in [25], an experimental measurement was performed investigating the time needed to get the Position Fixed Solution using DGPS services from the two Austrian RTK networks NETFOCUS and EPOSA. NETFOCUS is operated by EVN (Energier Versorgung Niederösterreich) with 12 permanent reference stations place among the area of Lower Austria. Measurement was performed by utilization of two different L2 GNSS receivers - Ashtec Mobile Mapper 100 and Ashtec ProMark 500. Measurement scenario was set up on the roof of the TU Vienna building in the center of Vienna city in Austria. Receiver was placed on the pillar No. 11 close to the roof which obstructed the measurements to get a better picture under ”real conditions”. Some results from the six test measurements taken with the Ashtec ProMark 500 are provided in the Figure 14. From the figure is obvious that any a priori data were missing in the first measurement taken. After the comparison of RTK Initialization Times among the all graphs, the similarity of the time durations since getting connected until getting fixed was noticed. Excluding the first measurement, the initial HRMS value was constant to ca. 20 cm among the next

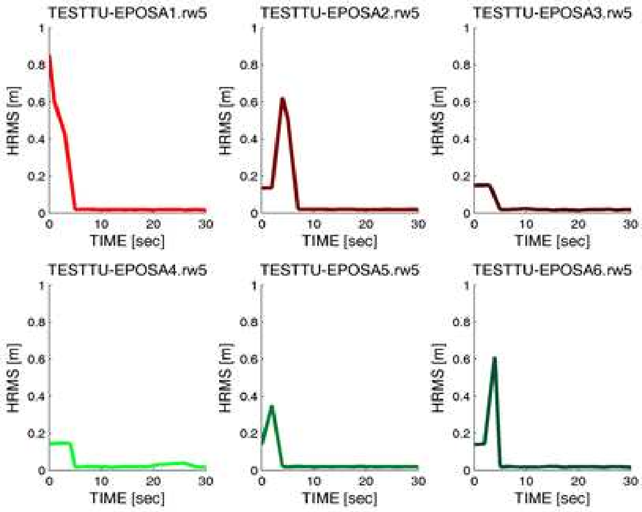

Figure 14: Initiazation of Ashtec ProMark 500 within EVN network.

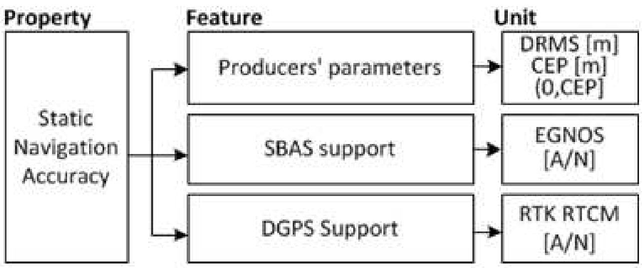

Figure 15: Static Navigation Accuracy Features of GNSS receivers.

five measurements. So it could be assumed that the latest available RTK data were used as the a priori values in the next measurement after the connection cut-off. Contribution of the a priori data to the initialization times speed-up were not observed. It could be assumed that all measurements behave by the same way - they reached a fixed solution determined from a priori value with a peak deviation in the state before. In further measurements, an exploration of possibility to get a fixed solution by only the internal antenna was performed. Measurement should show the length of initialization times for the EVN and for the EPOSA networks separately. Within this measurement no external antenna was used. The receiver Ashtec Mobile Mapper 100 was used for this purpose. Three measurements for each network were taken with no fixed solutions reached. Each measurement was therefore broken after 5 minutes.

From the measurements taken is obvious, that the quality of GNSS receivers can be measured also according to the length of DGPS RTK initialization times. This information is however provided neither by the GNSS chips manufacturers nor by the DGPS networks operators. It is also important to notice that external antenna is needed when performing RTK localization in slightly shaded real scenario.

In the Figure 15, there are summarized all features related to the Static Navigation Accuracy properties of GNSS receivers.

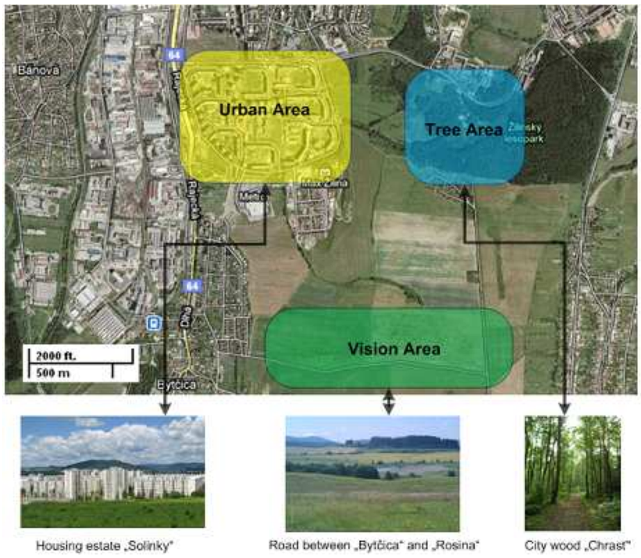

Figure 16: Tested track supplied with various physical conditions.

3.4 Dynamic Navigation Accuracy

Dynamic navigation accuracy can be in general described by the same features as the static navigation accuracy supplied with the parameters of receiver's surroundings emphasizing. Regarding [19], when it is considered the localization accuracy of moving objects (vehicles) the most important positioning parameters are physical influences of GNSS surveying. There are included systematic errors occurred within a range of GNSS receiver which are for different areas unique - Atmospheric effects, Multipath, Satellite shading. Since when the vehicle is moving, it obviously crosses areas with various surrounding conditions and its localization algorithms have to be coped with any kind of situation, e.g. barriers that could block clear view on the sky; passing over urban areas; occurrence of some unpredictable states of Atmosphere; etc.. Regarding the classification of the GNSS localization errors as mentioned in previous chapters, these systematic errors are also the sources of the highest localization inaccuracies.

For investigation of the impact of mentioned physical parameters on the localization accuracy as well as of their dependencies on the environment surrounding of GNSS antenna, a special tested track has been introduced. Selected area was located in Slovakia, in the town Žilina, and it was comprised from the parts "Solinky", "University of Žilina", "Žilinský lesopark" and "Bytčica". On the selected area was for the examination of impact of the surroundings parameters projected a tested track, which was divided into three parts - Urban Area, Tree Area and Vision Area (Figure 16). Urban Area was appointed for the analysis of multipath effect. It is located in the housing estate "Solinky" and it consists from several blocks of flats including also some higher buildings (30m). For the signal shading investigation was appointed the Tree Area located in the city wood "Chrast"'. It is the road that going through the forest and that is bounded by various, sometimes also about 40m high, trees that could block the GNSS signal. Vision Area is in point of fact the road between the city side "Bytčica" and the village "Rosina". It is located in the top of the hill, above all housing development with the clear view on the sky so it is ideal for estimation of the atmospheric effects. Projected track is

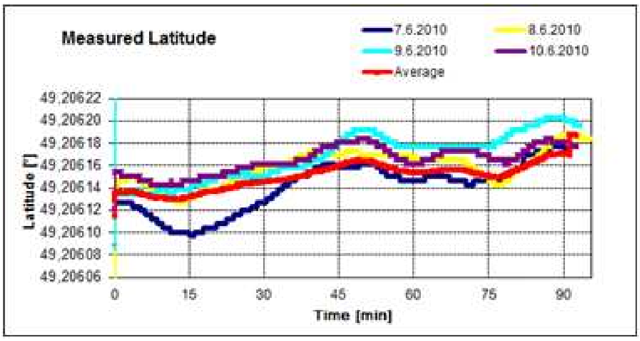

Figure 17: Measured results of measurement taken in 6th - 9th June 2010 / Latitude time behavior.

circa 6.3 km long, so for the steady move with the average speed of 5 km/h it is possible to go through in about 1.5h. To investigate the influence of the physical parameters of environment to the dynamic GNSS localization accuracy of a moving object, four experimental measurements were taken within this test track. The measurements wre taken in four 24-hours intervals in the time period of 6th - 9th June 2010 with the starting of localization data recording every day always at 13:00 ±1 min. For the simulation of the vehicle movement, the movement of a human with GNSS logger fixed into its belt was employed. After data logging started, the movement across the tested track started as well. As a measurement unit was chosen chip MediaTek MT3329 implemented in Holux M-1000C GPS receiver as usually. Except its high sensitivity, the possibility of the data recording into its 4MB embedded memory making almost 200 000 records possible was taken the advantage of too.

In every test run, the average speed of the "vehicle" was ca. 5 km/h and the track was finished in ±1.5h as expected. Tropospheric conditions were during the measurement almost the same with approximately homogenous weather, half-cloudy, with the temperature of +25 °C and atmospheric pressure ca. 1012 hPa. The measured result can be seen in the Figure 17. From the measurement results as shown in the Figure 17 is obvious that multipath effect and also the satellite shading interfered localization accuracy minimally since no significant changes between the movement across the Tree and Urban area were noticed and the size of deviations were almost same within all days for about ±1m in average. Considering the multipath effect, this happened probably because of the choice of unsuitable area for multipath testing. When comparing with urban areas in big cities (New York, Hong Kong,. . .), our was not overfilled with such high buildings so it can be assumed that the intelligent algorithms implemented in the control firmware of GNSS receiver handled these slight inaccuracies easily. As for the satellite shading, the trees were not so big obstructions because during the movement across the Tree Area, there were not recognized any significant satellite losses. It could be said, that during whole measurement it was used sufficient amount of satellites with very good DOP values (average HDOP of every satellite was 1.2) independently on the area of moving through. However, very important is that the space segment of the GPS consists at the present time of the boundary amount of satellites which can be increased only by the frequency change. This means that in every time in every location on the Earth at least 8 GPS satellites can be seen without considering the satellites from other systems. The differences between *Satellites_in_Use* and *Satellites_in_View* should be recalled here. In the time of the measurement neither Galileo nor GLONASS CDMA satellites were in use, so only the GPS satellites were applied. It could be also assumed, that algorithms integrated within the receiver can manage localization in lightly shaded areas without any big problems. Therefore, since no significant changes were noticed under the receiver's movement across the differently obstructed areas, the impact of atmospheric effect was assumed as the main source of the measurement inaccuracies. From the results can be also seen, that the tracks carried between 8th and 10th June are almost identical and they overlap each other. But the track carried on 7th June (blue line) is different. This was because of the distribution of TEC (Total Electronic Content) values measured by ESA in 6th-10th June 2010, where very poor conditions in Ionosphere on 7th June between 12:00 - 16:00 were observed. It could be then assumed that measurement taken on 7th June is such different because its localization process was disturbed by some significant change in Atmosphere (e.g. Solar Flare) which resulted to the GNSS signal delay. Influence of other systematic errors, such clock errors, relativistic effects and rounding errors, was eliminated by using of the unique GNSS receiver. The occurrence of orbital errors was eliminated because of the 24-hour periodicity of the measurement since the constellation of GPS satellites is the same after every 24 hours. What is really interesting is that this inaccuracy caused the prolongation of the track from 6.3 km to 8.6 km (!) as well as the acceleration of the average speed from 5 km/h to 6 km/h, whereas maximum determined speed was 44 km/h (!). These results would be very critical when considering SoL applications.

The previous measurements showed, also regarding [39], that if high quality, dual frequency GPS/GLONASS receivers and antennas are used in a differential mode (DGPS), taking advantage of both, pseudorange and carrier phase observables, localization accuracy in cm level can be reached. The question however was, how good is the performance of RTK in real conditions of a difficult environment. To analyze systematic effects such as multipath and related effects a measurement test-drive was performed in the urban area of Vienna city in Austria. The main aim of measurement was to investigate the performance of GNSS precise positioning technique applied to the localization of a moving object in difficult environment where the satellite signals were weaken by surrounding buildings. The test track within this experiment was however chosen to pass differently obstructed areas in the urban zone of Vienna consisted either of highly obstructed areas where critical satellite shading and multipath were expected or, on the other hand, of the roads with almost no obstacles that could block or somehow affect the satellite signal. This should allow to analyze the ratio of signal losses according to periods with fixed phase solutions. Except this, an impact of the vehicle's speed, multipath and other related effects on the RTK engine solution performance with emphasizing the environment where the measurement was being performed, could be investigated.

For this purpose, the measurement system consisted of the moving vehicle equipped with Topcon's GR-3 receiver and FC-250 field controller was introduced. Since the

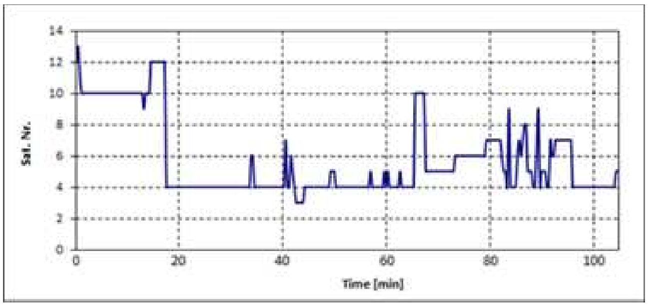

Figure 18: Number of utilized satellites recorded during the measurement taken on 21st of June 2011.

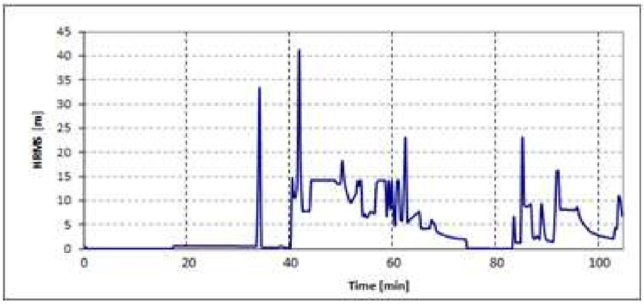

Figure 19: Horizontal RMS recorded during the measurement taken on 21st of June 2011.

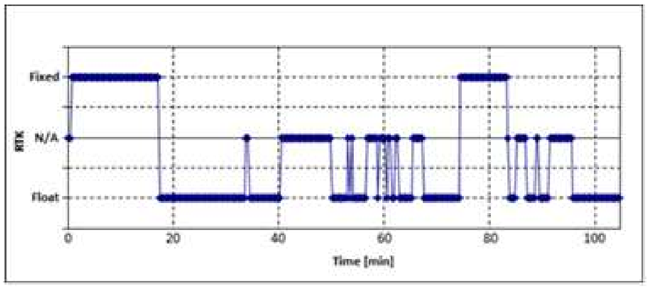

Figure 20: RTK solutions observed during the measurement taken on on 21st of June 2011.

receiver was able to track also the GLONASS FDMA satellites, the number of *Satellites_in_Use* should be as highest as possible. Positioning corrections in a real time were gained through the access to Austrian nationwide implemented RTK network EPOSA (Echtzeit Positionierung Austria) as in measurements before. The measurements taken at rover side were raw GPS and GLONASS observations adjusted via GPRS, 10Hz RTK service in RTCM 2.3 format with guaranteed cm localization accuracy during periods with fixed phase solutions. As it was already mentioned, the test track was chosen to pass differently obstructed areas in downtown Vienna. For better investigation of multipath effect, a drive in urban area of Vienna-Neubau was continuously repeated for circa 1 hour. Neubau is a heavily populated urban district, with a huge shopping area and residential buildings where the signal cancellation should be quite high.

Test drive was performed on 21st of June 2011 in 11:48 - 14:00 time period. From the test drive lasting about 2-hours, 6750 RTK positions as well as raw data files for post processing were gained. Due to problems with fixed solution acquiring, measurement was split into 2 phases each lasting ca. 1 hour. Tested vehicle was moving in a full traffic with an average speed of about 18 km/h, with the reached max speed 59 km/h. The distance of 39.6 km was completed in 1h 40 min with 29 minutes of stopped time. In the Figure 18 can be seen that the number of employed satellites during the measurement was circa 5 in average. This means that those satellites which were evaluated by GNSS receiver's algorithms as wrong for the localization process were filtered and disregarded. From the Figure 18 is also obvious that the number of used satellites was at the beginning, where upon the vehicle halt the fixed solution was acquired, quite high. Then after the movement started, receiver's algorithm blocked satellites predisposed to be affected by multipath. In the Figure 19, the horizontal accuracy observed during the measurement can be seen. From the figure is evident that number of satellites in use is not critical when RTK positioning is performed since the HRMS deviations values were quite volatile and no correlations between HRMS and *Satellites_in_Use* were observed. From the measurement is also obvious, that measured HRMS was good only until the time when the fixed solution was lost. After that, it was impossible to get the fixed solution again until the vehicle stopped for a longer time. It could be therefore assumed, that when the movement of vehicle is considered, once is the fixed solution lost, accuracy will improve back very slowly. In the Figure 20, the number of acquired fixed solutions during the measurement can be seen. From the figure is obvious that fixed solutions were acquired only two times. This was done only when the vehicle stopped for more than 3 minutes even at the place where no multipath was expected. Afterwards, when the movement started once again, the accuracy got worse until the fixed solution was fully lost. It could be therefore assumed that fixed solution strongly depends on the vehicle's movement together with the clear view on the sky. Summary of the all measurement results displayed in one graph is provided in the figure below. Correlations between vehicle's speed and RTK solution acquiring were during the measurement not observed. However, strong difficulties of fixed solution for a moving object in urban area acquiring were observed. From the measurement could be then concluded, that utilization of even the best GNSS receiver is for the vehicle movement within shaded city areas without additional sensors integration unsuitable. GNSS localization works correctly only when at least four satellites are within the receiver's line-of-sight. In many application scenarious such as in urban environments, in tunnels or in underground parking garages the view to the sky is obstructed. Integration of so-called augmentation methods is assumed to allow the receiver handle these situations [23].

Summary of the all measurement results displayed in one graph is provided in the Figure 21.

As regarding [21], dead reckoning (DR) provides relatively inexpensive way of GNSS augmentation. At the signal lost, it allows a vehicle by combining its speed and direction to continue its location estimating. The location calculated by dead reckoning usually become less accurate the longer is vehicle without GNSS signal since the displacement and heading errors accumulate over time. As regarding [26], methodology of Dead Reckonong is the base for the so-called Inertial Navigation. With regards to the definition in [47], the inertial navigation is a self-

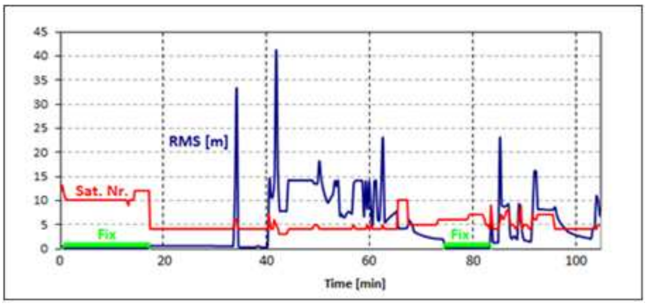

Figure 21: All measured results of taken measurement taken on 21st of June 2011 in one graphr.

contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity. Inertial measurement units typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration respectively [47]. By processing signals from these devices it is possible to track the position and orientation of a device. In order to achieve optimal dead reckoning performance, the GNSS and sensor measurements are combined using a tightly-coupled extended Kalman filter allowing for continuous and automatic calibration of unknown sensor parameters, such as bias and scaling factor of the gyroscope and the scaling factor for the wheel ticks representing the wheel's radius [41].

Variety of sensor techniques is used for detection of distance travelled. Odometer as well as wheel sensors can provide this information. Besides distance, the direction information is also necessary to be extrapolated from the travelled route. The gyroscopes are used for this purpose. MEMS gyroscopes are small sized providing good performance and are relatively inexpensive. In addition, a technique known as map matching can be used. Based on an actual position on the map, accumulated position and heading error can be mitigated by special application software. The quality of utilized map plays in any case the crucial role. As regarding [11], an approach of using the Dead Reckoning solution based on both GNSS and sensor measurements simultaneously together with map matching delivers the best result in urban environments where a wide range of signal conditions can be expected. The variations of Kalman filter algorithms are usually programmed in the GNSS chip to determine vehicle location based on weighted averages of multiple sensor data input provided by the GNSS receiver, wheel-ticks and gyroscope sensors [9]; [13]; [5]. Extended (EKF) and Unscented (UKF) Kalman Filters for nonlinear state estimation are utilized as the basics for these variations [12]. The output of the filter is an estimated position that lies in-between the predicted and measured values. Reached result is far more accurate than if just the single methods are used alone. This process is repeated iteratively, with the new estimate used in the succeeding calculation [28]. The measurements from the vehicle sensors are constantly calibrated during the periods of good GNSS signal reception. If situation with no or bad GNSS signal comes then up, GNSS continues to provide a quite accurate location based on the vehicle sensors' inputs.

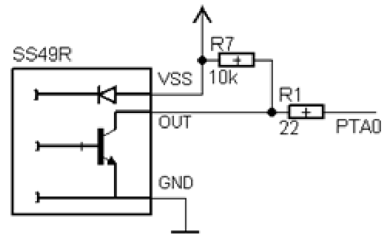

Figure 22: Hall Effect sensor design / simplified.

Though by integration of GNSS receivers into the INS system quite minimization of these errors could be achieved, extra-accurate navigation of moving object could be reached only by integration of other sensors based on different principles to avoid errors cumulating. When wheeled vehicles are taken into consideration, wheel-tick encoders supplied as a part of vehicle INS could serve this purpose. Different sensing methods are utilized in practice; following examples have been developed within the scope of this work [26].

- Reflective Optical Sensor with Transistor Output;
- Photo Interrupter;
- Hall-Effect based Sensor.

Since the photo sensors has been for practical use unsuitable, methodology of magnetic sensing has been introduced as an alternative. The digital Hall effect sensor was chosen as the base for the new INS sensor prototype. From the variety of products, Honeywell SS449R unipolar sensor with fast switching response about 1.5μs has been selected for this purpose. The sensor is operated by the magnetic field from a permanent magnet or an electromagnet designed to respond to a south single pole. Unipolar sensor was chosen due to the minimization of wheel slip influence on the INS accuracy. The simplified schematic of the sensing unit design is shown in the Figure 22. An open-collector NPN Transistor operates in its saturated region as a NPN sink switch which shorts the output terminal to ground whenever the applied flux density is higher than that when south pole is detected providing a push-pull output configuration that can sink enough current to directly drive microcontroller. The special coding wheel supplied with south-pole oriented magnets placed across its circumference will be delivered together with sensor to assure the proper functioning of the INS sensor. Since the communication within the whole INS is planned to be assured by CAN bus (Controller Area Network) utilization, proprietary microcontroller (MCU) has been chosen as the main control unit of the INS sensor. MC9S08DZ60MLF MCU provides sufficient solution integrating Freescale controller area network (MSCAN), with 40-MHz HCS08 CPU, 60kB flash and 4kB RAM. As the interface between a CAN protocol controller and the physical bus, PCA82C250 has been used for this purpose. The device provides differential transmit capability to the bus and differential receive capability to the CAN controller.

The sensor is the base for an experimental vehicle, which was developed in further steps. The vehicle will serve the purpose of testing platform for the GNSS receivers' quality investigation. The vehicle should be able to perform autonomous continual movement with very precise navigation output. Assisted technologies as A-GPS as well as SBAS integrated together with dead reckoning will allow very precise navigation when moving even across shielded areas. Integration of very precise etalon map is, however, assumed to be used for this purpose. The vehicle was constructed onto the squared, Aluminum chassis, using motors from accu-screwdrivers Asist H211-036i with max torsional moment ca. 250 min-1 with the epicyclical gear case included. Eight cylindrical magnets were placed and fixed evenly along the circumference of every wheel. This amount was sufficient for the purpose of our testing, however, utilization of special polarized magnetic stripes as used in ABS is assumed in the future. Since utilization of four separate DC motors has been assumed, the special quadruple high-power motor driver using VNH2SP30 motor driver integrated circuits from ST has been developed. The driver board combines most of the components of the typical application diagram regarding VNH2SP30 datasheet, including pull-up and current-limiting resistors and a FET for reverse battery protection. The VNH3SP30 is rated for up to 30A but is limited to about 9A maximum current without a heatsink. The motor controller supports forward, reverse, brake to ground, brake to Vcc and coast states. The speeds of the single motors can be controlled in all possible conditions by the microcontroller PWM (Pulse-width modulation) up to kHz.

For investigation of the experimental vehicle functioning, five experimental measurements each lasting about 1 hour have been taken in the "Vision Area" of tested track introduced in [19] on 29th March 2013. The vehicle was set up to the starting point after the all four wheels synchronized by performing of four turns tick over. Then after the GNSS receiver obtained the valid data from satellites, movement of the vehicle started. Since the variance of the error sizes had to be investigated, vehicle movement was performed across the constant track, defined by the constant values recorded to the main control unit of vehicle. So no mapping data has been used at the vehicle side. As the main control unit of the vehicle, Freescale demo board DEMO9S08DZ60 was integrated. Freescale board was used just like an interface between INS and personal computer where the GNSS receiver was assembled. During the measurement, the control board was collecting data from the sensors via CAN bus and subsequently transferring them to the laptop PC via serial interface. Wheel turns were sampled every 1 ms at 1 kHz rate using timer/counter interrupt of the microcontroller. GNSS measured positions were recorded into the internal memory of receiver at 1 Hz rate. Holux M-1000C was used for this purpose. No external antenna was used during the measurement. The vehicle was moving with constant speed always set to ca. 1.5 km/h by all four PWM channels of control microcontrolles.

The measurement results can be seen in the Figure 23 where the longitude time bahavior is depicted. The noteworthy improvement can be observed after the implementation of sensor fusion performed by using of an easy-to-implement Matlab function of Extended Kalman Filter for GPS published by [4] in post-processing. Since the movement within Easting direction was performed, longitude values became after the data filtration almost constant. It should be however mentioned, that the presence of an exact localization data is without RTK utilization

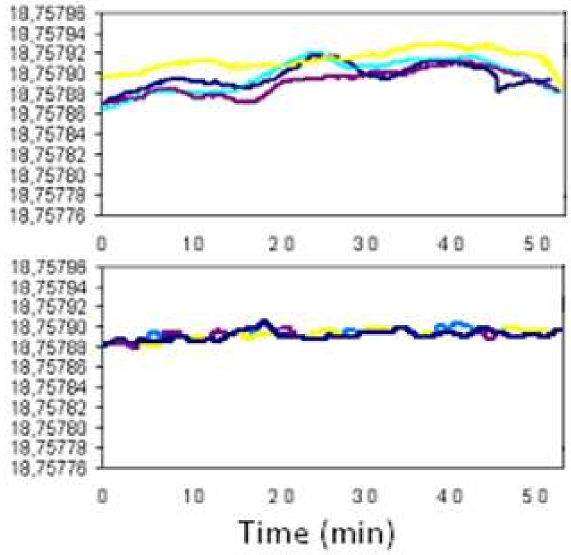

Figure 23: Measured longitude at the receiver's side from the measurement taken in 29th March 2013 / before and after application of EKF.

or without some etalon track map application impossible to prove. We can just prove that minimization of position deviations can be reached when using the vehicle's wheels for the track determination. Regarding the results reached within this work, the concept of the inertial navigation system, integrating CGEE A-GPS, SBAS EGNOS as well as RTK support has been introduced as the final outcome of this work (Figure 24). By integration of this system, the testing of the performance of various GNSS receivers when executing a dynamic movement under various environmental conditions can be done. The system is based on the developed INS platform and it defines the main control unit of the system based on 100 MHz ARM Cortex-M4 core MCU MK20DN512ZVLK1 with DSP instructions delivering 1.25 Dhrystone MIPS per MHz, program memory size of 512 KB and RAM memory size of 128 KB. The MCU peripherals include 10 low-power modes to provide power optimization based on application requirements, memory protection unit with multimaster protection, 16-channel DMA controller, supporting up to 64 request sources, external as well as software watchdog monitor and low-leakage wakeup unit. What is very important, the MCU includes eight-channel motor control/general purpose/PWM timer as well as the periodic interrupt timer necessary for the motor control of the vehicle. Broad number of communication interfaces, including USB full-/low-speed On-the-Go controller with on-chip transceiver, two CAN modules, two SPI modules, two I2C modules, four UART modules and I2S module, allowing integration of other supporting sensors.

The Quectel L20 L1 band GNSS receiver has been chosen as the GNSS engine module of the system. It comprises the SIRFstarIVTM chip solution with SIRFawareTM technology providing with -163dBm tracking sensitivity, -148dBm autonomous mode acquisition sensitivity, and quite low tracking power consumption. It allows to remove in-band jammers up to 80 dB-Hz and to track up to 8 CW jammers. With 48 PRN channels it can track satellites in a relatively short time even at indoor signal level. The support of EGNOS and CGEE is also obvious. The

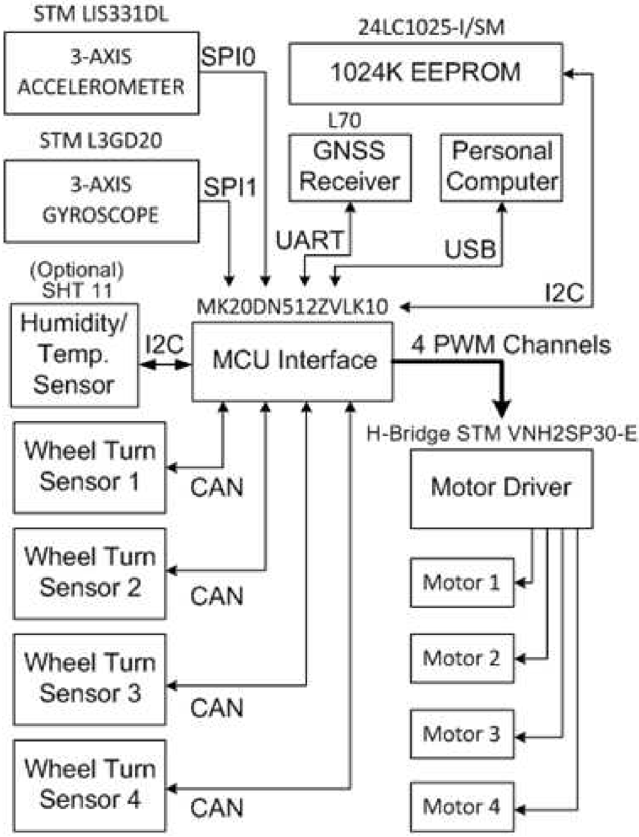

Figure 24: The concept of the experimental inertial navigation system.

module employs UART interface for communicating with the control MCU. Embedded I2C interface was utilized in CGEE interconnection with 1024K I2C CMOS Serial EEPROM 24AA1025 from Microchip. Utilization of the Freescale CAN interface in the frame of communication with the wheel-turn sensors was assumed to be implemented by the same way as in the measurement taken in 29th March 2013. Moreover, USB interface of MCU was used for interconnection with the laptop personal computer where positioning calculations performing EKF sensor fusion together with map matching could be made in a real time. Additional sensors as LIS331DL MEMS motion sensor 3-axis smart digital output accelerometer with ±2g/±8g dynamically selectable full-scale, capable of measuring accelerations with an output data rate of 100Hz or 400Hz as well L3GD20 MEMS motion sensor 3-axis digital gyroscope with three selectable full scales (250/500/2000 dps), 16 bit-rate value 8-bit temperature data output were implemented through serial interfaces SPI0 - 1. These sensors should allow versatility of the INS system especially when the developed control unit should be implemented on-board of different vehicle with the wheel-turn sensor output missing (train, ship, aircraft,...).

In the Figure 25, there are summarized all features related to the dynamic navigation accuracy properties of GNSS receivers.The performance of any GNSS receiver can be described by the all properties and features defined in previously. With respect to the expected final application, the requirements for the receiver's performance can be set and measured by the introduced units.

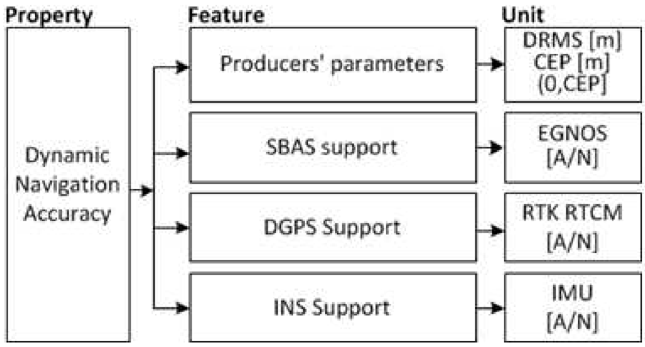

Figure 25: The concept of the experimental inertial navigation system.

4. Conclusions

Within this thesis, all GNSS based navigation and localization techniques for vehicle positioning have been investigated for potential implementation in ITS domain (Intelligent Transportation Systems). Various L1 and L2 GNSS receivers under the various environmental conditions were investigated emphasizing the localization quality reached among the single measurements. The analysis and classification of performance as well as an actual state-of-art of the single methods with respect to their characteristics and possibilities for using in vehicle positioning were examined. An analysis of the error sources and enhancement methods that can affect the quality of localization was made too.

The thesis deals with the identification and analysis of local surroundings parameters that could occur during localization process and could affect localization accuracy in various ways. This analysis was oriented mainly into the impact of factors that are reliant on the local environment surrounding of the GNSS antenna. From the realized measurements follows that from all identified GNSS accuracy affecting factors the highest distortion is caused by the atmospheric effect and multipath.

From all available GNSS enhancement techniques almost anyone was utilized and tested within this thesis, especially the impact of SBAS - EGNOS, A-GPS and D-GPS - RTK augmentations on the localization quality of the vehicle were analyzed. On the real examples, the influences of these techniques on the various parameters of the GNSS localization process were shown.

From the results demonstrated, the definition of all features necessary for the quality of GNSS receiver description was introduced. According to the GNSS receiver performance classification presented, the measurement quality of any GNSS receiver can be estimated. This allows the integration of the safety-relevant GNSS units into the specific applications of ITS since the information about the receiver's uncertainties will be available.

Furthermore, the concept of special vehicle for the testing of dynamic localization accuracy of moving objects has been also developed within this work.

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