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Establishment of a Local GNSS Correction Service for the Localization of Autonomous Vehicles

Szabolcs Rózsa[1a], Ágnes Ács[1], Bence Turák[1]

[1] Department of Geodesy and Surveying, Faculty of Civil Engineering, Budapest University of Technology and Economics

[a] Corresponding author: rozsa.szabolcs@emk.bme.hu

Abstract

Accurate localization of autonomous vehicles is a key component of the onboard control and guidance system. Global Navigation Satellite Systems (GNSS) are widely used in the transportation industry for positioning and navigation, but the generally used single point positioning (SPP) technique cannot meet the accuracy requirements of the autonomous vehicles. This paper briefly introduces other GNSS positioning techniques with the accuracies ranging from several meters to centimeters. The techniques are compared in terms of accuracy, latency and reliability. Highly accurate positioning techniques usually rely on a groundbased augmentation system (GBAS) that provides correction services for the users. We introduce the procedure and the first results of establishing a local GNSS correction service at the ZalaZONE Automotive Proving Ground. The results show that cm level positioning accuracy can be achieved with such a service in real-time that enables the users to track the trajectory of the vehicles with high accuracy.

Keywords: *DGNSS, GNSS, RTK, SPP*

1 Introduction

Determining the positions of observing sites on land, at sea, or in the air using observations of distant objects has been carried out for hundreds of years. However, it was only with the space-age and the appearance of artificial satellites that it became possible to develop a global system for high accuracy positioning and navigation. As a result, the global navigation satellite system (GNSS) was established. A historical review of the evolution of satellite-based positioning can be found in [1].

The principle of satellite-based positioning is the spatial trilateration process using ranges measured to satellites with known positions. GNSS receivers record the run time (τ_S) required for the signal to reach the receiver from the satellite antenna. This time interval can be easily converted to range by multiplying it by the speed of light. When the known position vector of the satellite is denoted by ρ^S and the unknown position vector of the receiver is ρ_R, the measured range takes the form

$$\rho_R^S = \|\rho^S(t-\tau_S) - \rho_R(t)\|, \tag{1}$$

where both vectors are relative to the geocenter. Since the satellite and receiver clocks are not synchronized, the receivers observe the so called pseudoranges:

$$P_R^S = \rho_R^S + c(dt_R - dt^S), \tag{2}$$

where dt_R and dt^S denote the clock offsets of the receiver and the satellite (transmitted by the satellites). Thus, at least four satellites are needed to determine a kinematic 3D position, since the receiver clock error is unknown and it is changing rapidly.

The fundamentally harmonic radio wave GNSS signals (termed the carrier) are modulated with a characteristic pseudorandom noise (PRN) code and with a low-rate navigation data message. This enables two methods to measure the pseudoranges to each satellite. Using the code ranges (C/A code) to observe the pseudoranges one can achieve an accuracy of approximately 3 m and the observation is unambiguous. On the other hand, using the carrier phase without the codes, one can improve the accuracy of the pseudoranges to several mm. However, phase range observations are ambiguous, only the fractional wavelength can be measured with such an accuracy and the integer ambiguities – the number of full waves between the satellite and the receiver – must be resolved during the position computation. In the next sections we will introduce the fundamental GNSS positioning techniques, that could be used for positioning autonomous vehicles.

2 GNSS positioning techniques

In this paper we aim to present various positioning techniques tested in a real case study to assess their characteristics and accuracy measures. Approximately 2 hours of GNSS observations taken by a static low-cost U-blox F9P multi frequency multi GNSS receiver are processed with each positioning technique. The measurements were processed with the RTKlib open-source software [2] using GPS, Glonass, and Galileo dual-frequency observations.

2.1 Single point positioning

The equation of absolute positioning with code ranges is the following:

$$P_i^j(t_i) = \rho_i^j(t_i - \tau_i^j, t_i) - c\delta t_i(t_i) + c\delta t^j(t_i - \tau_i^j) + T_i(t_i) + I_i^j(t_i) + v_{P_i^j}, \quad (3)$$

where P_i^j is the measured pseudorange (between satellite j and receiver i), ρ_i^j is the geometric distance between the satellite and the receiver. $c\delta t^j$ is the effect of satellite clock error, which is transmitted as part of a navigation message broadcast by the satellites. T_i and I_i^j denote the effect of the troposphere and the ionosphere on signal propagation. In real-time applications without any further information, these effects can be mitigated using the correction models defined either in the navigation messages or by empirical functions. More information about clock errors and the effects of the atmosphere is available in [3] or in [4].

Fig. 1 shows the time series of the horizontal coordinate residuals. One can observe that the spread of the position solutions is in the order of several meters. The GPS system provides the horizontal position accuracy of less than 13 meters at the 95% probability level (2σ) in 24 hours anywhere on the globe [5]. Our results shows a much lower uncertainty in the study period mostly because of the inclusion of the additional satellite systems.

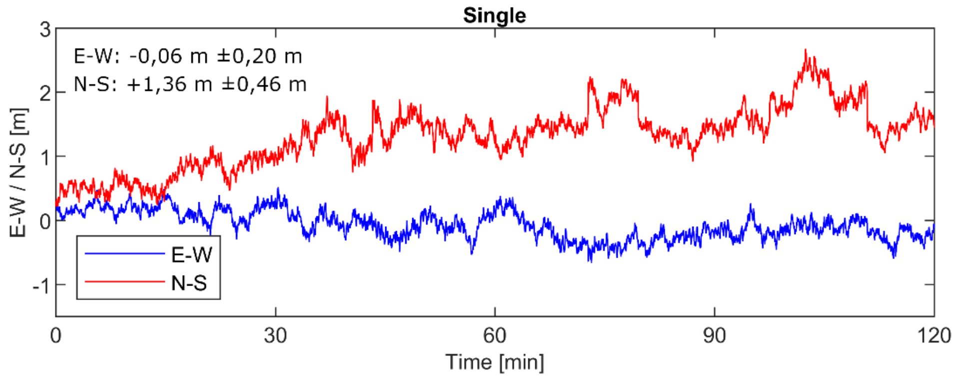

Fig. 1 *Absolute positioning with code ranges (120 minutes of results)*

2.2 Differential positioning with code ranges

Although SPP technique meets the requirements of navigational applications, several positioning applications of moving platforms require significantly higher accuracy, such as the guidance and control of autonomous cranes or the tracking of autonomous vehicles. The SPP technique has several limitations. Satellite clocks are synchronized on the level of ca. 5ns leading to a ranging error of ca. 1.5m, broadcast orbits has the accuracy of ca. 1m and other systematic error sources like ionospheric delays are not modeled on an accuracy level to achieve submeter positioning accuracy, To overcome this problem, the differential positioning technique was introduced (DGNSS). DGNSS uses additional simultaneous observations provided by a base station to reduce the effect of the mentioned systemic error and to improve the accuracy of the positioning in real-time. The base receiver is installed on a site with known coordinates and it tracks all the available GNSS satellites in view. By taking the pseudorange observations the base receiver is capable to calculate the pseudorange residual using its own coordinates and the known position of the satellite:

$$\Delta P_b^j(t_i) = \rho_b^j(t_0, t_i) - P_b^j(t_i) = c\delta t_b(t_i) - c\delta t^j(t_i - \tau_i^j) - T_b^j(t_i) - I_b^j(t_i). \quad (4)$$

This pseudorange residual contains information on the effect of the troposphere and the ionosphere, the orbit error and the clock biases of the satellite and the base receiver. The pseudorange residuals (corrections) are transmitted to the rover receiver in real time to correct the observations of the rover receiver:

$$P_r^j(t_i) + \Delta P_b^j(t_i) = \rho_r^j\left(t_i - \tau_r^j, t_i\right) - c\delta t_{br}(t_i) - \Delta T_{br}^j(t_i) - \Delta I_{br}^j(t_i) \tag{5}$$

Thus, one obtains a similar equation to (3), but the systematic error sources are either eliminated or significantly reduced. It must be noted that DGNSS positioning technique can be solved with exactly the same algorithm as SPP using the corrected pseudorange observations. Fig. 2 shows the results of the differential positioning relative to ground truth in our case study. The results show that submeter level accuracy can be achieved with this technique without the need for initialization, so the position solution is available instantly after observation gaps. Moreover one can observe that the experienced coordinate uncertainties are much lower compared to the SPP case reaching the sub-meter level.

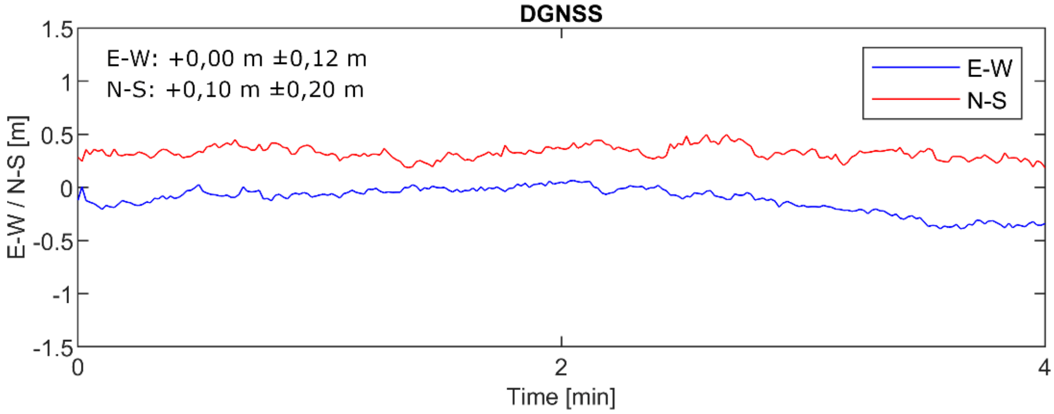

Fig. 2 *Differential positioning with code ranges (first 4 minutes of results). The statistics show results of 120 minutes of observation.*

2.3 Relative positioning with carrier phases

In case of the relative positioning technique the PRN (pseudo random noise) codes are removed from the modulated signal and the pure carrier signal is used to measure the satellite-receiver distance. The carrier waves have the wavelength of ca. 20 cm. GNSS receivers create a replica of the carrier wave and compare this replica with the received carrier wave signal to measure the phase angle difference between them. This phase angle difference enables us to measure the fractional distance (within one λ) with high accuracy. However, the number of full carrier waves between the satellite and the receiver is still to be found. Thus the equation of phase ranges are as follows:

$$\Phi_r^j(t_i) = \rho_r^j\left(t_i - \tau_r^j, t_i\right) - c\delta t_r(t_i) + -c\delta t^j\left(t_i - \tau_r^j\right) + \lambda \cdot N_r^j + T_r^j(t_i) - I_r^j(t_i) + v_{\Phi_r^j}(t_i). \tag{6}$$

where N is the phase ambiguity. Let's assume that one observes m satellites in s epochs in a kinematic application. Since the number of unknowns is $m+(3+1+m)\times s$ (m phase ambiguities and 3 coordinates, 1 receiver clock error and m satellite clock error per epoch) and the number of observations is only $s\times m$, the numerical solution of this problem is impossible. In case of PPP (Precise Point Positioning) additional high accuracy satellite clock offsets are introduced in the calculation to decrease the number of unknowns [2]. Another method is to use the relative positioning technique and eliminate the quickly changing receiver and the satellite clock error.

Similarly to the DGNSS positioning, the position of the receiver could be determined relative to a base station. Calculating the difference of the observations of the two receivers at the same epoch for each satellite the single-difference of phase ranges are obtained:

$$\begin{aligned}\Delta\Phi_{b,r}^j(t_i) &= \rho_r^j\left(t_i - \tau_r^j, t_i\right) - \rho_b^j\left(t_i - \tau_b^j, t_i\right) - c\delta_r(t_i) + c\delta_b(t_i)\\ &+\lambda \cdot \left(N_r^j - N_b^j\right) + [T_r(t_i) - T_b(t_i)] + v_{\Phi_{b,r}^j}\end{aligned} \tag{7}$$

This equation gives the vector between the base and the rover receiver. Unfortunately the receiver clock error values are still changing rapidly over time causing a large number of unknows. To eliminate them, double differences are calculated by differencing the single differences with respect to a reference (pivot) satellite:

$$\Delta\Delta\Phi_{b,r}^{j,k}(t_i) = \rho_r^k(t_i - \tau_r^k, t_i) - \rho_b^k(t_i - \tau_b^k, t_i) - \rho_r^j(t_i - \tau_r^j, t_i) + \rho_b^j(t_i - \tau_b^j, t_i) + \\ + \lambda \cdot (N_r^k - N_b^k - N_r^j + N_b^j) + [T_r^k(t_i) - T_b^k(t_i) - T_r^j(t_i) + T_b^j(t_i)] + v_{\Phi_{b,r}^{j,k}} \quad (8)$$

In our example the number of double differences is $s \times (m-1)$, and $3s+(m-1)$ unknown parameters must be determined. Although the relative position vector can not be solved from observations taken in a single epoch, it can be solved using several epochs of observations. It must be noted that despite ambiguities (N) are integer numbers by definition, they can be only estimated as real numbers (float solutions), and they must be resolved in a subsequent step as integers (fixed solutions) to achieve cm accurate positions [3]. Fig. 3 shows the initialization part of solving kinematic relative positioning in our case study. One can clearly see the initialization phase of the positioning, and how the accuracy improves after fixing the ambiguities. Other results of using phase ranges in vehicle tracking can be found in [6] and [7].

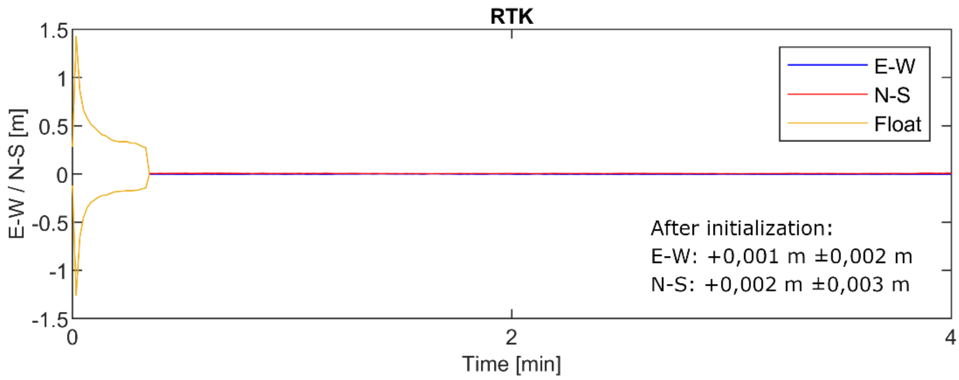

Fig. 3 *Relative positioning with carrier phases (first 4 minutes of results). The statistics show results of 120 minutes of observation and only fix solutions.*

Summarizing the various positioning techniques, one can see that SPP and DGNSS techniques has the advantage of providing instantaneous positioning solutions, while RTK and PPP has a longer initialization (convergence) time. Although RTK technique provides cm accurate coordinate solutions after fixing the ambiguities, it also needs a certain initialization time after each signal loss to achieve this accuracy level. The positioning solution accuracies show that DGNSS technique is capable to provide lane level positioning accuracy with quick response time, thus it is ideal for vehicle tracking applications on the Proving Ground. However, the accuracy of RTK positioning is required for both dynamic testing applications and the development of the localization techniques of autonomous vehicles. Based on the comparisons it is clear that a ground based augmentation service is fundamental for the operation of the ZalaZONE Automotive Proving Ground. In the next section we will briefly introduce the establishment of such a station at ZalaZONE.

3 ZalaZONE permanent station

We have seen that several positioning technique used in vehicle tracking applications need correction services provided by a fixed permanent reference station. To assist the testing of vehicle dynamics and autonomous control and driving algorithms at the ZalaZONE Automotive Proving Ground, a dedicated reference station has been established. The station consists of a Leica GR30 geodetic multi-GNSS receiver capable to track all the available GNSS and SBAS (Satellite Based Augmentation Systems) satellites including GPS, GLONASS, Galileo, Beidou and EGNOS. The station is equipped with a Leica AR20 geodetic antenna manufactured with choke ring elements to mitigate multipath effects (Fig 4). The phase center offset and variation of the antenna has been determined using the absolute chamber calibration technique developed at the Geodetic Institute of the University of Bonn [8]. Thus, the equipment fully complies with the quality standards of the European (EUREF) Permanent Network.

The GNSS station provides three different correction streams through the NTRIP (Networked Transport of RTCM via Internet Protocol) broadcaster of the Department of Geodesy and Surveying at the Budapest University of Technology and Economics. The broadcast streams are:

- ZZON0 providing RTCM 3.2 MSM7 (RTCM Multiple Signal Messages v7) GNSS correction for GPS/GLONASS/Galileo and Beidou satellites realizing the highest accuracy corrections available;
- ZZON1 providing RTCM 3.2 corrections for GPS and GLONASS satellites only due to compatibility issues for older receivers;

- ZZON2 providing RTCM 3.2 MSM4 (RTCM Multiple Signal Messages v4) GNSS corrections for GPS/GLONASS/Galileo and Beidou satellites realizing GNSS corrections with a lower transmission bandwidth a lower accuracy with respect to ZZON0.

Fig. 4 *The ZZON Permanent Station at the ZalaZONE Automotive Proving Ground*

The station coordinates have been determined using weekly observations of nearby EPN reference stations using the Bernese GNSS processing software V5.2 [9]. The station coordinates have been calculated in the European Terrestrial Reference Frame (ETRF2000) and refers to the epoch of the 2007.4, which corresponds to the geodetic datum of the Hungarian Active GNSS Network (GNSSNet.hu). Thus, the GNSS correction service seamlessly fits to the national GNSS correction service provided by the GNSSNet.hu. The station coordinates are given in Table 1. One must note that differential and relative positioning techniques provide coordinate solutions in the reference frames used to defined the reference station coordinates, while absolute positioning techniques provide solutions in the WGS-84 (World Geodetic Systems 1984) or ITRS (International Terrestrial Reference System) global reference frames. Currently the lateral difference between the continental ETRF and the global WGS-84/ITRS coordinates is close to one meter.

Table 1 *The ETRF2000 (Epoch 2007.4) coordinates of the ZZON station*

X	4179601.3173
Y	1264445.0024
Z	4633710.2155

4 Outlook

The permanent GNSS reference station becomes a fundamental infrastructure of the ZalaZONE Automotive Proving Ground. However, it can play an important role in the maintenance of the Hungarian and the European geodetic infrastructure, too. The station currently holds the status of being a proposed station in the EUREF Permanent Network and transmits realtime corrections to the EUREF-IP network as well as provides hourly and daily observations for the geodetic community. The observations are routinely processed not only to obtain repeated coordinate solutions of the stations for quality monitoring purposes, but also to use the information content of the GNSS signals for remote sensing atmospheric water vapour to improve the accuracy of weather prediction.

In the near future we plan to include the permanent GNSS station in the Hungarian Active GNSS Network, too.

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