The Potency of the Modernized GNSS Signals for Real-Time Kinematic Positioning

Dhota Pradipta[1], Heri Andreas[1], Dina A. Sarsito[1], and Hendy F. Suhandri[2]*

[1]Geodesy Research Group, Faculty of Earth Sciences and Technology, Institute of Technology, Bandung, Indonesia

[2]Coastal, Ocean and Maritime Engineering Research Group, Faculty of Earth Sciences and Technology, Institute of Technology, Bandung, Indonesia

Abstract. GNSS positioning has become popular in the past decade as an efficient method of precise and real-time positioning. It is relatively low cost and ease-of-use. Up to now, several parameters were defined to characterize the performance of real-time positioning: availability, precision, accuracy. This article evaluates the performance of signal linear combinations for real-time positioning, both for static as well as the kinematic positioning. This article starts with the investigation of linear combinations (LC) rising from the carrier frequencies of the GNSS systems. Some Linear Combination shows potential benefits in carrier phase integer ambiguity resolution, particularly utilizing the Galileo and Beidou signal phase carrier. For each system, a set of combinations was studied, analyzed, and then selected during the development of GNSS positioning method utilizing the Least-squares Ambiguity Decorrelation Adjustment (LAMBDA). Special signal selection can affect the estimated position and its standard deviation. To further analyze, the results obtained from data processing are compared with respect to baselines and signals. The ambiguity fixing rate is correlated with the baseline length and the method as well as the signals that were used. The analysis of the measurement noise level was first conducted to set a baseline for the real-time GNSS positioning application. According to the results and to assess the data quality and positioning performance of GNSS in respect with GPS (Global Positioning System), an experimental test has established using MGEX data. This research investigates the satellite visibilities, multipath, Signal to Noise Ratio (SNR), and positioning performance. It is shown that in every epoch, at least 8 satellites are visible. The SNR's are up to 60 dBHz, the code multipath residuals varies within ~1 m, while the phase residuals varies by about ~2 cm. hence the modernized GNSS signals have potencies to improves the RTK positioning.

1. Introduction

Satellite based navigation technology is continuously and rapidly growing in recent time. The Global Navigation Satellite System (GNSS) are Galileo System (GAL) and BeiDou System (BDS), which is developed and operated by European Union and China. Currently, GAL and BDS is entering the third phase of development that is expected to enhance the positioning performance will continue to the final phase on 2020 with global coverage of positioning and navigation system by a constellation of 35 satellites, which are consists of 5 Geostationary Earth Orbit (GEO) satellites, 3 Inclined Geosynchronous Orbit (IGSO) satellites and 27 Medium Earth Orbit (MEO) satellites [1]

Similar to GPS, GAL and BDS provides triple-frequency signal. Table I gives the frequencies and wavelengths of the signal from the GAL and the BDS as well as the GPS.

Differs from GPS, BDS adopts the China Geodetic Coordinate System 2000 (CGCS2000) as the coordinate system and BeiDou navigation satellite system time (BDT) as the time system of BDS. GAL using Galileo Terrestrial Reference Frame (GTRF) and Galileo System Time (GST). CGCS2000 is a global, three-dimensional, right-handed, orthogonal, geocentric coordinate system which referred to ITRF97 (International Terrestrial Reference Frame 97) at the epoch 2000.0.

Table 1.1 Parameters of WGS84, CGS2000, GTRF ellipsoid

	WGS84	CGCS2000	GTRF
a (m)	6 378 137.000	6 378 137.000	6 378 137.000
f	1/298.257223563	1/298.257222101	1/298.257223563
GM (m^3s^{-2})	3.986005 E 14	3.986004418 E 14	3.986004418 E14
Ω (rad s^{-1})	7.292115 E-5	7.292115 E-5	7.292115 E-5

---

* Corresponding author: dhota@fitb.itb.ac.id

The ellipsoid used in CGCS2000 is slightly different from WGS84 (World Geodetic System 1984) as seen on Table II. Theoretically, the differences induced by those ellipsoids is within 1 millimeter in the equator [1]. BDT adopts seconds without any leap seconds as the international system of unit (SI). The BDT's start epoch was 00:00:00, 1 January 2006 of Universal Time Coordinated (UTC). In respect with GPS Time (GPT), BDT is 14 s ahead GPT (BDT = GPT + 14 s) [1].

Table 1.2 Frequencies and wavelength of GNSS signals (GPS, Galileo, and Beidou)

Satellite System	Signal	Carrier frequency (MHz)	Carrier wavelength (cm)
GPS	L1	1575.42	19.03
	L2	1227.60	24.42
	L5	1176.45	25.48
GAL	E1	1575.42	19.03
	E5a	1176.45	25.48
	E5b	1207.14	24.83
BDS	B1	1561.098	19.20
	B2	1207.14	24.83
	B3	1268.52	23.63

Several studies have been conducted in several areas, particularly in northern hemisphere. The combination of GPS, GAL, and BDS can increase the observation data quality as well as the positioning performance [1].

With a highly growth of infrastructure in Indonesia, the use of GNSS technology is inevitable, especially for the surveying and mapping purposes. Further research over GNSS data quality and positioning performance in Indonesia is needed. To assess the data quality and positioning performance GNSS in respect with GPS (Global Positioning System) over Indonesia, an experimental network had established using MGEX data. This research investigates the satellite visibilities, multipath, Signal to Noise Ratio (SNR), and the positioning performance.

2. Data Quality Assessment

In order to investigate the advantages of GNSS, the satellite visibilities were analysed. Better satellite visibilities lead a better geometry of satellites constellation, namely Dilution of Precision (DOP), which introduces to a better position accuracy and precision.

DOP can be divided into several terms, which are vertical DOP (VDOP), horizontal DOP (HDOP), position DOP (PDOP) and time DOP (TDOP). Those terms can be generalized by using Geometric DOP (GDOP) term. In order to achieve the highest position accuracy and precision (low DOP value), the satellites geometry is not supposed to clustered together in a single quadrant.

Fig. 2.1 shows the number of observed satellites for GPS, GAL, BDS, and combined systems with a cut off angle of 10°. It can be found that the satellite visibilities of GNSS combinations is more stable than the GPS. By using GNSS, at least 10 satellites can be observed for more than 80% of observation time., while the number of combined systems observed satellites is vary from 12 to 22 with an average of 14 satellites.
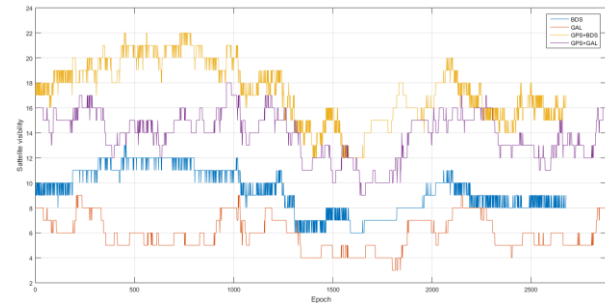

Fig. 2.1 Satellite visibility

2.1 Multipath

This section described the methods that used to assess the data quality of GNSS.

The multipath of GNSS can be investigate by applied the Multipath Combination (MPC) algorithm. The MPC can be expressed as [6]:

$$MP1 = P_1 - \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2} B_1 + \frac{2f_2^2}{f_1^2 - f_2^2} B_2 \tag{1}$$

$$MP2 = P_2 - \frac{2f_1^2}{f_1^2 - f_2^2} B_1 + \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2} B_2 \tag{2}$$

where *P* and *L* are the GNSS pseudorange and carrier phase range respectively and *f* is the frequency of the carrier phase. By using these combinations, the first order of ionospheric delay and geometric range from satellite and receiver are eliminated, while noise is assumed to be negligible due to the accuracy of the pseudorange observation.
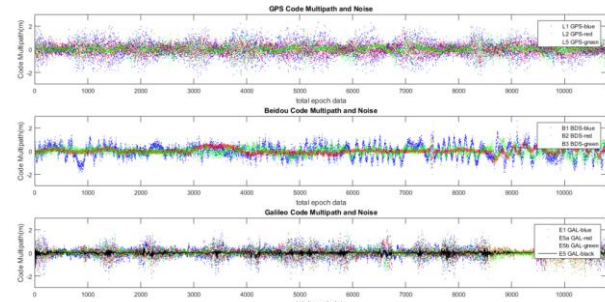

Fig. 2.2 Code Multipath for GNSS signals (GPS, Glonass, Galileo, and Beidou)

2.2 Signal to Noise (SNR) Ratio

Concerning satellite configuration, site-specific factors as well as atmospheric effects, the quality of GNSS observations may become inconsistent and affecting SNR. In addition, observation weighting plays a dominant

role when GNSS receivers calculate positions by measuring pseudo-distances to transmitting satellites. A GNSS receiver performance mainly depends on the signal power in the receiver's tracking loops [2].

There are several methods to measure the GNSS signal strength. However, as the data sent by GNSS are through radio signals, it is a known fact that radio signals cannot maintain their strength for longer distances. The GNSS system employs phase modulation to superimpose data on the radio signals for better reception by the GNSS receiver and the manufacturers employ different algorithms to retrieve the data from the signals for offering the desired data.

All the factors correlating with the elevation angle of the transmitted GNSS signals like the SNR normally grow with increasing satellite elevation angle. SNR is usually expressed in decibels and it refers to the ratio of the signal power and noise power in a given bandwidth. Due to the fact that noise and signal are amplified in the same way, these ratios can be expressed as [3]:

$$\frac{C_{ant}}{N_{ant}} \approx \frac{S_{corr}}{N_{corr}} \approx S \qquad (3)$$

Signal to noise ratio can usually be found in the context of signal baseband of the modulated signal at correlator output (S_{corr}). The quality of a received GNSS signal is commonly described by carrier to noise ratio of the modulated carrier at the receiving antenna (C_{ant}). The system noise affects the signal quality and the noise and signal are amplified in the same way in the antenna (N_{ant}) and at the correlator output (N_{corr}). As the system noise is several magnitudes smaller than C_{ant} and S_{corr}, therefore the values are normally converted to decibels (dB) to represent a specific bandwidth, thus:

$$S(dB) = 10.log_{10}(S) \qquad and \qquad (4)$$

$$SNR(dB) = S/N \qquad (5)$$

Assuming the GNSS signal strength is S and the noise level is N, the basic formula to measure the GNSS signal strength is S/N. If the carrier waves facing obstructions, S will get affected by attenuation, because many signals have a very wide dynamic range and are expressed using the logarithmic decibel scale, signal and noise may be expressed in decibels (dB). Assuming the system noise (N_0) is several magnitudes smaller than the signal strength (S), the normalized signal quality is [3][4]:

$$SNR\ (dBHz) = S - N = 10.log_{10}(S)(dB) - (N_0.B_L)(dBHz) \qquad (6)$$

The user should be careful when comparing different GNSS receivers, particularly for older models e.g. Trimble that provided the signal quality in "arbitrary manufacture unit" (AMU). AMU units are dependent and need to be converted by a conversion formula because the value can differ by up to 3 dB from the original value [4]. Different generations of GNSS satellites have inherently

different signal strengths, which could cause different SNR values with nothing wrong at all.

Different GNSS receivers with the same antenna tracking the same satellite at the same time may provide different SNR values. These differences could be from band limitation or processing algorithms. In case of independent acquisition and tracking algorithms used by a receiver, the values could be considered to indicate the quality of the received signal when antenna and receiver type, design, and performance are neglected. Hence the SNR depends on the receiver bandwidth, signal acquisition and tracking parameter.

In order to analyze the behavior of SNR and code multipath/noise, all GNSS signals were processed. By using an epoch by epoch method, each epoch was processed to get SNR and code range residuals and then an averaging method was adapted to get mean values for the figures.
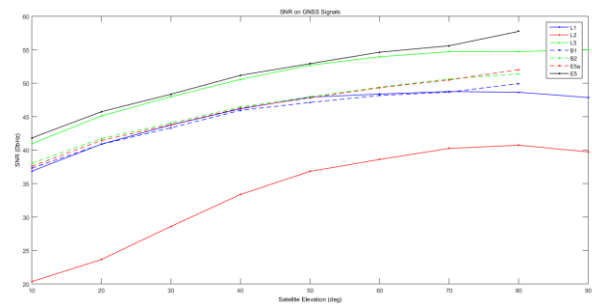

Fig. 2.3 SNR mean of GNSS signals (GPS, Galileo, and Beidou)

In case of the E1 Galileo signal, the SNR and the code multipath/noise residual seems to perform higher than the L1 GPS with up to 1-2 dBHz for signal strength and up to 0.1 m for residual difference, refer to figure 2.2 and 2.3. On the other hand, E5 Galileo performs best in SNR and code multipath/noise residuals at every station tested. When selecting promising signals for future real-time positioning, the combined E5 Galileo signal emerges as one of the alternatives (better than E5a) when using Galileo signals.

Because multipath errors are site-specific and particularly affect the code ranges, the use of E5 Galileo provides an advantage, as this signal shows a low multipath/noise residual behavior compared to all other GNSS signals. Moreover, due to its higher signal strength, the E5 Galileo signal is preferable for positioning because the signal is more resilient against outside interference than other GNSS signals and offers advantages to mitigate multipath/noise and ionospheric errors.

3. Performance Test

3.1 Relative Positioning

The performance of relative positioning was analyzed by using double difference (DD) positioning using carrier phase range that constructed by differencing two single

difference (SD) observation. SD can be described as follows [6]:

$$\Delta L^j_{A,B} = \Delta \rho^j_{A,B} + d^j_{tropA,B} - d^j_{ionA,B} + c(dt - dT)^j_{A,B} + + ML^j_{A,B} + \lambda N^j_{A,B} + \vartheta L^j_{A,B}$$

(7)

where Δ is the difference between receivers A and B. The superscript -j is the observed satellite. The satellite clock error is eliminated by taking single difference between receivers that observed the same satellite, while the atmospheric biases like tropospheric and ionospheric may be eliminated depending to the length of the baseline. Multipath would be considered as a noise error that could not be eliminated.

The remaining receiver clock error is then eliminated by subtracting two single difference observation. Mathematically, a DD is defined as follows:

$$\nabla \Delta L^{jk}_{A,B} = \Delta \rho^{jk}_{A,B} + + ML^{jk}_{A,B} + \lambda N^{jk}_{A,B} + \vartheta L^{jk}_{A,B}$$

(8)

where the two satellites are denoted as he superscript-j and k. The atmospheric biases are negligible in Eq.8, however the noise error is multiplied up to two times with respect to SD.

By using MGEX data, we assumed that the precision of GAL and BDS are similar with GPS for all of the position components using DD method in kinematic solutions. The precision of the horizontal and vertical components is in cm level. The ambiguity fixing rate of GPS, BDS, GAL, and combined are more than 90% with the coordinate differences w.r.t. GPS solutions are in cm level (~2 cm)

3.2 Ionosphere Free Linear Combination

Several linear combinations could be introduced beside the standard L1/L2 GPS ionosphere-free linear combination [2][9]. Moreover, it is even possible to design useful triple frequency linear combinations from all frequencies in GNSS. As the ionospheric delay is dispersive, the phase observables delay of Φ_i can be related to the delay of Φ_j by the known ratio of wavelengths of the two observables:

$$i_j = (\lambda_j^2 / \lambda_i^2) i_i$$

(9)

where the two observables are in order, $\lambda_j > \lambda_i$, and the ratio can be denoted as:

$$\frac{\lambda_j}{\lambda_i} = \frac{t}{n}, t > n$$

(10)

where both t and n are (positive) integers. Using the wavelength ratio, the ionosphere free linear combination ϕ_{ij} of two observables is obtained as:

$$E\{\phi_{ij}\} = \frac{t^2}{t^2 - n^2} E\{\phi_i\} - \frac{n^2}{t^2 - n^2} E\{\phi_j\}$$

(11)

Introducing the integer ambiguities N_i and N_j (11) can be detailed as:

$$E\{\phi_{ij}\} = \rho + \frac{t^2}{t^2 - n^2} \lambda_i N_i - \frac{n^2}{t^2 - n^2} \lambda_j N_j - \left(\frac{t^2}{t^2 - n^2} - \frac{n^2}{t^2 - n^2} \frac{t^2}{n^2}\right) i_i + e_{ij}$$

(12)

The range of observable ρ appears in the same way as in the original phase observation equation. Moreover, the ionospheric delays are eliminated $\left(\frac{t^2}{t^2 - n^2} - \frac{n^2}{t^2 - n^2} \frac{t^2}{n^2}\right) i_i \approx$ 0, and a combined ambiguity term remains, which does not seem to be integer valued. However, using equation (12) with t and n integer, it is possible to rewrite the ambiguity term to be:

$$E\{\phi_{ij}\} = \rho + \frac{t^2}{t^2 - n^2} \lambda_i (tN_i - nN_j) + e_{ij} = \rho + \lambda_{ij} N_{ij} + e_{ij}$$

(13)

where λ_{ij} denotes the artificial wavelength and N_{ij} the integer ambiguity of the ionosphere free combination and e_{ij} denotes multipath and noise values.

A consequence of taking the ionosphere-free linear combination is that the noise of the ionosphere-free observable is increased compared to the noise of the original phase observations. When it is assumed that two original observables are uncorrelated and have same precision $\sigma_{\Phi_i} = \sigma_{\Phi_j} = \sigma_\Phi$ in DD mode, the variance of LC follows:

$$D\{\phi_{ij}\} = \frac{t^4 + n^4}{(t^2 - n^2)^2} \sigma_\Phi^2$$

(14)

where $D\{\phi_{ij}\}$ denotes the mathematical dispersion.

Denoting the greatest common divisor as c, we may write for the numerator and the denominator of the wavelength ratio $t = c \cdot t_c$ and $n = c \cdot n_c$, where c ≥ 1.

3.3. Data Processing and methodology

Table 3.1 Data for data processing

Observation Data (RINEX) DOY (280, 2017)	CEBR-VILL IGS (35 km) GPS+GLO+GAL+BDS+SBAS
IGS data precise orbit file	IGS (pre)
Auxiliary data (updated using data from NGS)	antenna information file receiver information file satellite problem file noise model parameter file information coordinate file

The processing strategy was designed as follow:

- The following calculations were carried out using data from observation, i.e. 1 hour of observation Rinex data 1 second sampling rate. Calculations were also carried out with Glonass signals (if available) during similar observation

periods in equal satellite geometry. Integer ambiguities are estimated and resolved on an epoch-by-epoch basis in kinematic positioning mode.

- The initial scenario assumes all the observations are processed in difference mode. Hence, the atmospheric errors and clock errors are taken into account. To create a scenario with different baseline, the data were sorted out by the stations to arrange the conditions required. As the local time and the location of the test are essentially affecting the results due to variations in the ionosphere and troposphere activity, calculations of the measurement effect on same time window sessions were performed.

- Mask angles of ten degrees were selected. The receiver noise level was neglected, and when required, IGS precise orbit corrections were used for reference. Tropospheric effects are also independent of frequency. And using a standard model correction.

- Furthermore, the observations were grouped in short-term observations (less than and equal to 60 minutes) for positioning for static(reference) and kinematic positioning.

- Additionally, since most observation data covers satellites with low elevation angles, observation to satellites which are below 10 degrees are removed to minimize the influence of errors in the data processing.

- The distance between base and rover was up to 40 kilometers.

- Ionosphere free linear combination and the MLAMBDA method was used to estimate the carrier phase ambiguities [5][8].

4. Results

Result from data processing shows that a combined signal (GPS+BDS and GPS+GAL) can be improved the resolution time when the GEO satellites is introduced for ambiguity fixing in case of obstruction problems.

Based on the results, it is shown that in every epoch, at least ten satellites of GNSS are visible. The SNR for BDS vary within 25-55 dBHz (figure 3) which is less power than other GNSS signals, the code multipath variation of all GNSS signals varies within ~1 m, while the phase residuals variation varies up to ~3 cm. In addition, a GNSS modernized signal has better precision compared with L1/L2 GPS, and the combined used of GPS+BDS and GPS+GAL improves the solutions on positioning, particularly on kinematic positioning.

Figure 4.1 and 4.2 shows the estimated kinematic position with GNSS data. To further analyze, the pseudorange and the carrier phase residuals obtained from observation are compared. The figure shows that there is similar accuracy up to 2 cm. According to the figure 4.1 and 4.2, all signals provides similar results position (about 2 cm of position deviation) to L1/L2 GPS solution as reference. However, the Galileo gives a smooth pattern of result. On the other hand, when combination signals were processed, a combination between GPS+BDS displays a slightly good trend with respect to L1/L2 GPS comparing with other combinations.
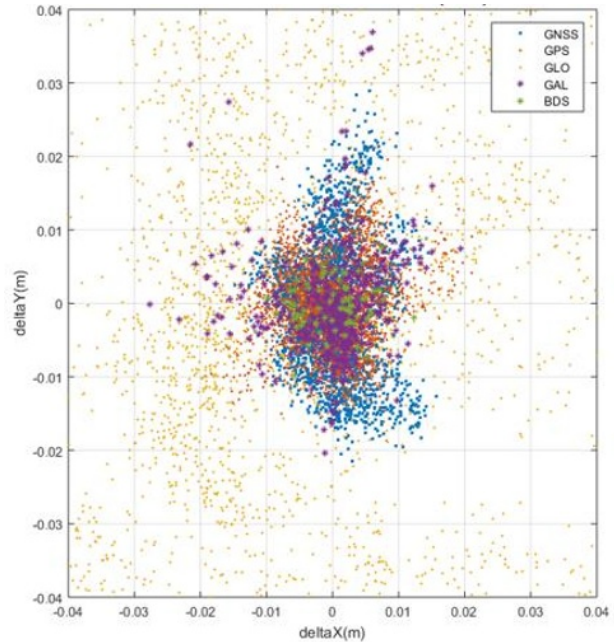

Fig. 4.1 Kinematic Solution from GNSS sateliltes with baseline up to 35 km (GPS, Glonass, Galileo, and Beidou)
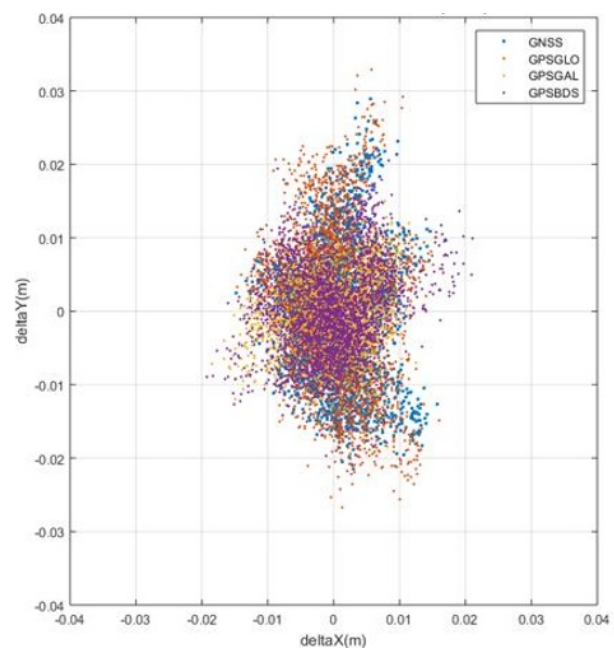

Fig. 4.2 Kinematic Solution from GNSS satellite combinations with baseline up to 35 km (GPS, Glonass, Galileo, and Beidou)

The residual level normally increases at the VILL-CEBR baseline with 35 km, as not all the ambiguities could not be fixed completely by utilized all satellites within observation time span. However, there is a systematic residual pattern in the code and phase residuals which indicates systematic noise that affected the position result (refer to figure 4.3 and 4.4).
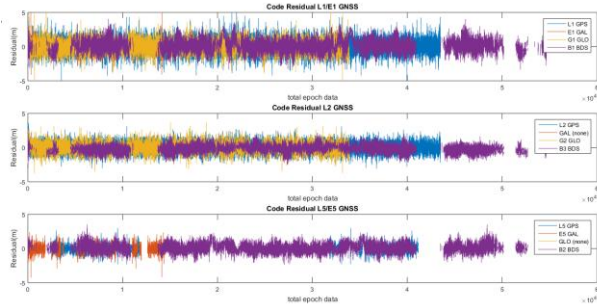

Fig. 4.3 Code Residual from GNSS satellite signals (GPS, Glonass, Galileo, and Beidou)

These characteristics can open the possibility of performing code-range measurements using modernized GNSS signals at the decimeter level and enable a better mitigation of multipath effects, particularly for signal combination with small code residuals.

Fig. 4.3 shows code residuals for all available satellites. By taking a large number of all satellite observations, the code multipath/noise residuals for L5 and E5 are smaller than L1/L2 GPS residuals. On average, the L5 and E5 provides ~1 m deviation. However, by using L5 and E5 signals are allowed more accurate combined code-and-carrier observable to mitigate ionospheric errors because it has the strongest signal strength of the modernized GNSS signals tested.
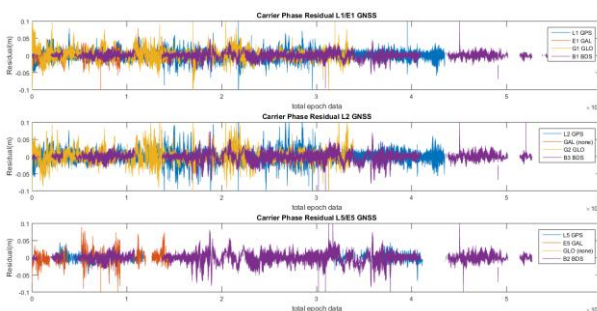

Fig. 4.4 Phase Residual from GNSS satellite signals (GPS, Glonass, Galileo, and Beidou)

Fig. 4.4 shows carrier-phase residual for medium baseline (35 km) from experiment test (MGEX data). Good solutions were possible due to several available signals and satellites. Hence, the utilization of GNSS data as combined signal. GPS, GAL, BDS, and its combination provides similar results that varies up to 5 cm for kinematic positioning.

the standard deviation of the coordinate time series shows interesting features (figure 4.5). The dual carrier phase combination, particularly from Galileo observable performs extremely well. It is mostly better (less than 2

cm) than the L1/L2 GPS standard deviation of ionosphere-free linear combination. On the other hand, the standard deviation of the L1/L5 GPS-LC and B1/B2 BDS-LC corresponds with the L1/L2 GPS pattern. A short time observation (at least 60 minutes) seems to be sufficient to resolve the ambiguity for kinematic positioning up to 40 km compared with the GNSS ionosphere free linear combination in case of the VILL-CEBR baseline with a length approx. 35 km. With a modernized GNSS system, the E1/E5 Galileo linear combination seems to perform much better than the other frequency combinations. However, when insufficient Galileo observations are not available (less than 5 satellites) the standard deviation becomes worse than L1/L2 GPS.
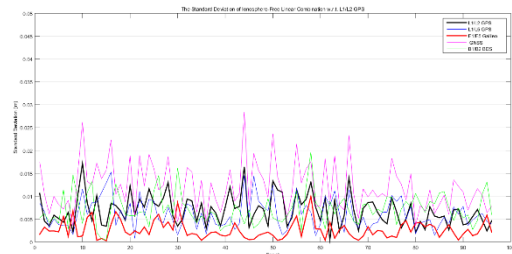

Fig. 4.5 Standard deviation from GNSS satellite combinations for baseline up to 35 km (GPS, Glonass, Galileo, and Beidou)

5. Conclusion

This research has been conducted to study the performance of the GNSS real time positioning technology introducing modernized signals on medium baseline, and by means of a free software application. Most of the investigated signal linear combinations are capable to deliver accurate, precise and consistent position solutions, although they perform differently in terms of noise, ionospheric content and ambiguity resolution ability. This research focuses on single baselines observed over short to medium periods.

Because multipath errors are site-specific the rover environment has to be chosen carefully. In case of evident multipath the E5 Galileo delivers an advantage compared to other signals due to its more multipath resistant codes which also goes in parallel with a higher received signal strength. Other unencrypted signals provide similar SNR-values with a difference of approximately 1-5 dBHz and range noise in zenith direction of up to 0.25 m. On the other hand, the GPS L2 signal in this research shows the lowest SNR value with differences up to 10 dBHz and zenith range noise up to 0.4 m.

The standard deviation of the position differences using GNSS dual frequency data of several minutes (up to 60 minutes) is very close to the L1/L2 GPS solution. Galileo and Beidou signals can be used as advanced substitute and simultaneously in case of insufficient or improper L2 GPS observations. Need to be taken into account, the results are of course affected by the number of available satellites, satellite geometry, and observation time spans.

Modernized GNSS signals deliver a potency to provide best performance in static and kinematic positioning. Compared to GPS L1/L2 a clear advantage to use Galileo and Beidou linear combination becomes apparent in order to reduce signal noise and multipath significantly with reveals biases up to a few centimeters (~2 cm). These offsets might be caused by un-modeled intersystem biases between GPS, Galileo, and Beidou signals.

References

[1] Hofmann-Wellenhof, B., Lichtenegger, E. Wasle. (2008). GNSS-Global Navigation Satellite Systems. Springer, Wien.

[2] Odijk, D. (2003). Ionosphere-Free Phase Combinations for Modernized GPS. Journal of Surveying Engineering Vol. 129. November

[3] Rost, C. and Wanninger, L. (2009). *Carrier Phase multipath mitigation based on GNSS signal quality measurements.* Journal of Applied Geodesy 3, de Gruyter, pp. 1-8. DOI 10.1515/JAG.2009.009.

[4] Amiri-Sikooci, A., Tiberius, C., C., J., M. (2007). Assessing Receiver Noise Using GPS Short Baseline Time Series. GPS Solution, Vol. 11. Pp21-35 DOI 10.1007/s10291-006-0026-8.

[5] Davaine, M. (2011). Code Bias and Multipath Estimation with Cascaded Kalman Filter. Thesis. Insitute for Communication and Navigation, Technische Universitaet Muenchen. Munich, November.

[6] Xu, G. (2007). GPS Theory, Algorithms and Application. Berlin: Springer.

[7] Joseph, A. and Petovello, M. (2010). Measuring GNSS Signal Strength. Inside GNSS. November, pp. 20-25.

[8] Teunissen, P. J. G., (1995). The Least-square Ambiguity Decorrelation Adjustment: A Method for Fast GPS Ambiguity Estimation. Journal Geodesy, vol.70.

[9] Richert, T., and N. El-Sheimy (2007). Optimal linear combinations of triple frequency carrier phase data from future global navigation satellite systems. GPS Solutions, Vol. 11, No. 1, pp. 11-19. DOI 10.1007/s10291-006-0024-x.