Estimation of Snow Depth From GLONASS SNR and Phase-Based Multipath Reflectometry

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***Abstract*—Monitoring snow variations can know how fast the snow is melted and how much water is frozen on the Earth. However, traditional ground techniques have some limitations to monitor snow variations due to high cost. Recently, global navigation satellite systems-reflectometry (GNSS-R) has been developed and used to sense snow variations, while previous studies mostly used global positioning system (GPS) observations to estimate snow depth. In this paper, snow depth is estimated from GLONASS signal-to-noise ratio (SNR) and phase-based multipath reflectometry at one IGS GANP station in Slovakia, which is compared with *in situ* observations. For two snow seasons, snow depth estimations from GLONASS SNR1 and SNR2 data have a good agreement with *in situ* results with correlations of 0.94 and 0.94 in 2012 and 0.92 and 0.89 in 2013, respectively. Compared to GPS results, snow depth results from GLONASS are almost similar, but have some differences due to low coverage of less GLONASS satellites. However, results from GLONASS geometry-free linear combination (L4) are not pretty much, which needs more works to improve it in the future. Combined GPS and GLONASS observations have no significant improvement on the precision, but improve the spatial resolution because of more satellites.**

***Index Terms*—Global navigation satellite systems-reflectometry (GNSS-R), GLONASS, global positioning system (GPS), signal-to-noise ratio (SNR), snow depth.**

I. Introduction

SNOW variations play an important role in water cycle. However, because of the high temporal and spatial variability, it is difficult to monitor large-scale snow variations from traditional ground-based techniques such as manual and automated methods [1], [2]. Global navigation satellite systems (GNSS) have been widely used for positioning, navigation, and timing. In addition to these typical applications, recently, new remote sensing applications have been developed, including atmospheric and ionospheric sounding [3] and GNSS-reflectometry (GNSS-R) for land and ocean monitoring [4]. A number of GNSS-R theories and models have been developed and demonstrated in land and ocean applications [3]–[5]. The GNSS-R is different from the typical navigation and positioning application with only using the direct signal, while it also employs the reflected signal. Therefore, the typical GNSS receivers normally cannot be employed for above applications, which need new GNSS receivers or equipments to receive the reflected signals. Since the frequency of GNSS multipath modulations is changing with the variation of antenna heights, the snow depth can be obtained from the relationship between signal-to-noise ratio (SNR) and antenna heights. Recently, geodetic global positioning system (GPS) receivers were demonstrated as a remote sensing tool by Larson *et al.* [6], namely GPS multipath reflectometry (GPS-MR). Snow depth was estimated using GPS L2C SNR data, which showed a good agreement with *in situ* snow depth [7]. Some other studies using GPS L5, L2P, and L2C signal with a dipole antenna have been tested [8]–[10]. Furthermore, snow density using GPS-MR method was also retrieved [11].

In addition, Jin and Najibi proposed another method to estimate snow depth using the geometry-free linear combination of the GPS phase measurements (L4) based on the nonparametric bootstrapping model [12]. Compared to the L4 method, the SNR method employs the frequency of multipath modulations to retrieve snow depth, and the different part is the way to extract GPS multipath.

However, previous studies mostly used GPS observations to estimate snow depth. Recently, the GLONASS system has more and more satellites with increasing observations. More importantly, most IGS stations can also receive GLONASS signals excluding GPS signals. In this paper, snow depth is estimated from GLONASS-multipath reflectometry. GLONASS SNR and L4 observations are used to retrieve snow depth, and their performances are compared and accessed at one IGS station with co-located meteorological data and both tracking GPS and GLONASS signals in Slovakia. Furthermore, it is compared with GPS as well as combined GPS and GLONASS results.

II. Theory and Methods

A. SNR Method

The carrier-phase, pseudorange, and SNR are the main observables of GNSS, while the SNR observable is not always available when compared to the other two. SNR is usually used to assess the signal quality and the noise characteristics of typical GNSS surveying, which can be calculated by the ratio of the signal power to the measurement noise. For RINEX files, SNR measurements can be extracted directly as the form of $\mathrm{S1}/\mathrm{S2}$ in decibel (dB) units. In order to improve the development of near-surface reflectometry, Nievinski and Larson have presented one multipath forward model described as [13]

$$\mathrm{SNR} = (P_d + P_r + P^I)P_n^{-1} + 2P_n^{-1}\sqrt{P_d P_r}\cos\varphi \qquad (1)$$

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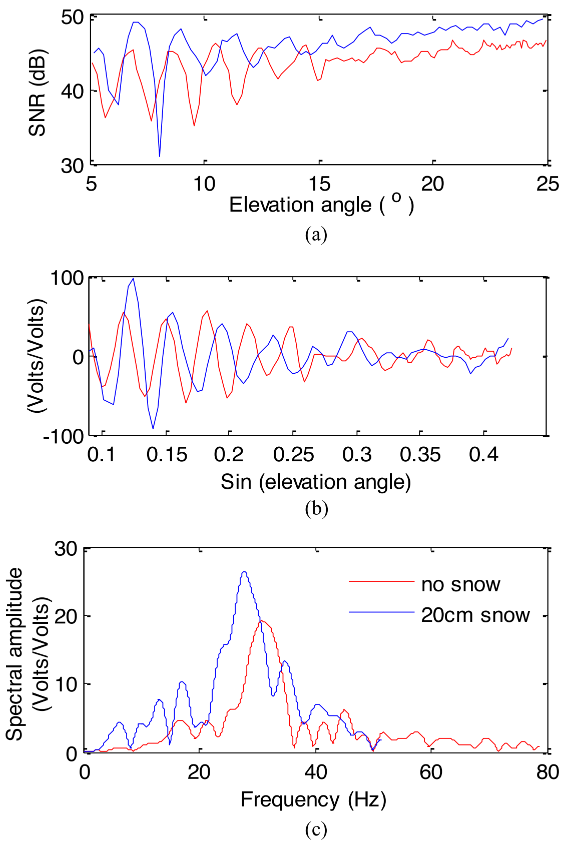

Fig. 1. (a) GLONASS SNR1 observations from PRN9 satellite on November 2, 2011 (red) and February 4, 2012 (blue). (b) Multipath modulations in (a). (c) Lomb–Scargle periodogram of multipath pattern in (b).

where P_d is the direct power, P_r is the reflected power, P^I is the incoherent power, P_n is the noise power, andφ is the interference phase. In (1), $2P_n^{-1}\sqrt{P_d P_r}\cos\varphi$ is the interference fringe causing the oscillations in SNR observations [see Fig. 1(a)]. The oscillation, also called multipath effect, is the interference between direct and reflected signals when they are received at the same time by GNSS receivers. Although the reflected signal will be suppressed by the antenna gain of geodetic-quality GPS receivers, it still can be received at low satellite elevation angles (5–30°) [14]. For multipath reflectometry, the incoherent power P^I and coherent power $P_d + P_r$ without the interference are useless and should be removed. After removing the SNR trend, the multipath pattern can be obtained and modeled as [14]

$$\mathrm{SNR} - P_d + P_r + P_r^I)P_n^{-1} = A\cos(4\pi H\lambda^{-1}\sin e + \phi) \quad (2)$$

where A is the amplitude, H is the antenna height, λ is the carrier wavelength, e is the satellite elevation angle, and ϕ is the phase. The multipath pattern is expressed as cosine of sine of the elevation angle e, showing the periodic multipath pattern [see Fig. 1(b)]. The frequency of multipath modulations is related to the antenna height, so the relationship can be written as

$$H = \lambda f/2 \quad (3)$$

where λ is the wavelength and f is the frequency of GNSS multipath pattern. When the surface is covered by the thick snow, the reflector height will be changed, which affects the

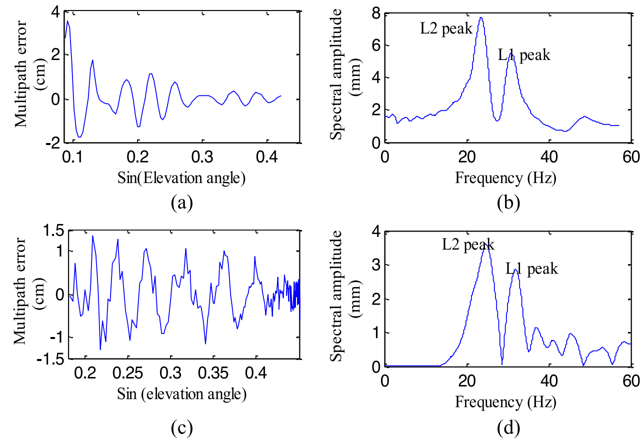

Fig. 2. (a) L4 multipath simulation. (b) Lomb–Scargle periodogram for simulation. (c) L4 multipath error from GLONASS PRN22 satellite on November 2, 2011. (d) Lomb–Scargle periodogram for observation in (c).

frequency of GNSS multipath modulations. Therefore, the main parameter to estimate the snow depth variations is the frequency of multipath. In order to get the frequency, the Lomb–Scargle periodogram method is used [see Fig. 1(c)]. From Fig. 1(c), it is also clear to see that multipath patterns with different snow depths correspond to different frequencies.

B. *L4 Method*

Although it is convenient for the SNR observable to extract multipath modulations, it is not always available in raw GNSS data because of less applications for most GNSS users. As we know, the GNSS phase observation for double-carrier L1 and L2 signals can be expressed as

$$L_1 = (\phi_1 + N_1)\lambda_1 = \rho + I(f_1) + T + M_1 + \mathrm{noise}_1 \quad (4)$$

$$L_2 = (\phi_2 + N_2)\lambda_2 = \rho + I(f_2) + T + M_2 + \mathrm{noise}_2 \quad (5)$$

where ϕ_1 and ϕ_2 are the phase measurements, λ_1 and λ_2 are the wavelengths, ρ is the true geometric range between the satellite and receiver, T is the tropospheric delay, $\mathrm{I}(f_1)$ and $\mathrm{I}(f_2)$ are the ionospheric delay for L1 and L2 signals, N_1 and N_2 are integer ambiguities for L1 and L2 signals, and M_1 and M_2 are the multipath errors. For the GLONASS system, double-carriers are L1 and L2 signals, and the difference can be written as

$$L_4 = L_1 - L_2 = I(f_1) - I(f_2) + M_1 - M_2 + \mathrm{noise}_1 - \mathrm{noise}_2. \quad (6)$$

From (6), the L4 combination cancels geometric information in GNSS observations and only retains non-geometry parts such as ionospheric residual, multipath, and other noises. Therefore, L4 combination can be used to extract multipath if other items can be removed.

In order to remove the ionospheric delay and other noises, a high-order polynomial (here 14-order polynomial) is used to fit the L4 observable, and then the multipath pattern will be obtained [see Fig. 2(a) and (c)]. Although most ionospheric residual can be detected by the high-order polynomial, there are still some residuals, which are difficult to remove. Using the simulator proposed by Nievinski and Larson [16], we simulated the L1 and L2 phase multipath errors for GLONASS and then combined them [see Fig. 2(a)]. This simulator is presented mainly for GNSS-multipath reflectometry, which considers different surfaces and antenna types with due consideration for polarization and coherence. From (6), it is clear to see that the multipath error derived from L4 observables is the combination of L1 and L2 phase multipath errors, so two peaks (L1 and L2) are shown in Fig. 2(b). The two peaks can also be seen in the Lomb–Scargle periodogram for the L4 multipath pattern from GLONASS PRN 22 satellite [see Fig. 2(d)], which is the same with the simulated results. For the phase multipath, a phase shift related to the total received microwave signal (i.e., reflected plus direct signals) can be modeled as [15]

$$\delta\phi = \tan^{-1}\left(\frac{\alpha\sin(4\pi H\lambda^{-1}\sin e)}{1+\alpha\cos(4\pi H\lambda^{-1}\sin e)}\right) \quad (7)$$

where α is the reflection coefficient depending on the reflectivity of the ground (snow) surface and the antenna gain pattern, H is the antenna height, λ is the wavelength, and e is the elevation angle. From (7), we know that the frequency of phase multipath pattern is related to the antenna height, so the relationship in (3) is appropriate for phase multipath if we simplify (7). On the other hand, the L2 peak is much clearer than L1 peak through the simulation, so we use the frequency of L2 peak to retrieve snow depth.

III. Observation Data

GLONASS has been developed by Russia, originally started by Soviet Union in 1976. The GLONASS space segment is composed of 24 satellites over three orbital planes (separated by 120 right ascension of the ascending node) with radius equal to 25 500 km and 65° inclined angles [3]. For the channel access method, GLONASS is different with GPS. The signal broadcasted by GPS satellites is distinguished by the code division multiple access technique, while the technique for GLONASS is frequency division multiple access, meaning that the frequencies of signal broadcasted by different satellites are different. The signals used in this paper are L1 and L2 with initial frequencies of 1602 and 1246 MHz. However, the final frequencies of L1 and L2 signals broadcasted by different satellites depend on the frequency channel. Currently, there are 24 operating satellites of GLONASS, so the visible satellites are comparable to GPS. About nine satellites are available for most epochs, so enough observations can be used to estimate snow depth.

One IGS station in Slovakia with both tracking GLONASS and GPS and available *in situ* measurements is used to estimate snow depth, i.e., GANP station (altitude: 49.034, longitude: 20.323, Height: 745.20 m). The TRIMBLE NETR9 receiver and TRM55971.00 antenna with no external radome are used, so the new L5 signal can also be tracked. In order to estimate snow depth, GNSS observations from two snow seasons are employed: one is from November 2011 to March 2012 and the other is from September 2012 to April 2013. Fig. 3 shows the antenna of GANP station, whose height is 2.8 m. The co-located climate station for GANP is the Poprad station (Height: 696 m), which is 6.5 km away from GANP site. Because of the similar elevation, snow depth data from Poprad station can be representative for GANP station. The daily *in situ* snow depth data are available from the website (www.weatheronline.co.uk), while not every day has snow depth data.

Fig. 3. Antenna of GANP station in Slovakia.

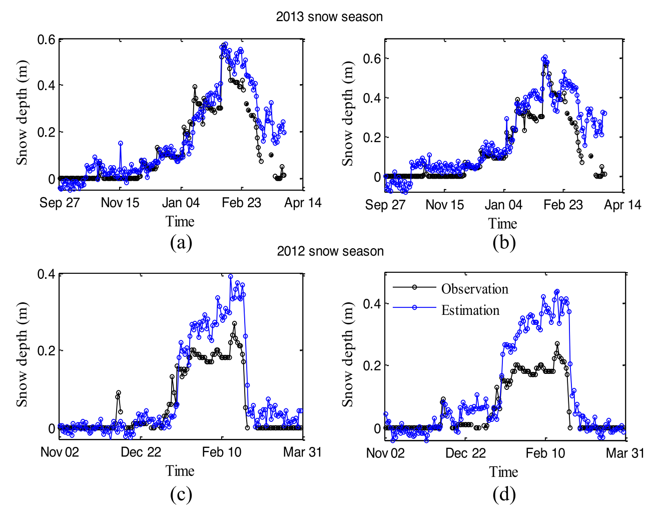

Fig. 4. Snow depth from GLONASS SNR estimations and *in situ* observations in 2012 and 2013 snow seasons.

IV. Results and Analysis

Here, the GLONASS SNR and phase observations (L1 and L2) are both used to estimate the snow depth, which is also compared with *in situ* snow depth observations from two snow seasons.

A. SNR Results

Fig. 4(a) and (b) shows the comparisons of snow depth estimations and *in situ* observations in 2013 snow season, and both SNR1 and SNR2 results have an good agreement with *in situ* observations. SNR estimations have the peak height in February 2013, which is same with *in situ* observations. During

TABLE I
CORRELATION AND RMSE BETWEEN ESTIMATIONS AND OBSERVATIONS

Snow season	GNSS system	observation	Correlation Coefficient	RMSE (m)
2012	GLONASS	SNR1	0.94	0.06
		SNR2	0.94	0.09
	GPS	SNR1	0.93	0.05
		SNR2	0.89	0.07
	Combined SNR		0.95	0.06
	GLONASS	L4	0.54	0.08
	GPS	L4	0.71	0.07
	Combined L4		0.65	0.07
2013	GLONASS	SNR1	0.92	0.07
		SNR2	0.89	0.09
	GPS	SNR1	0.87	0.07
		SNR2	0.89	0.07
	Combined SNR		0.93	0.060
	GLONASS	L4	0.64	0.13
	GPS	L4	0.66	0.12
	Combined L4		0.65	0.11

the end of snow season, both SNR1 and SNR2 estimations are higher than *in situ* observations. This circumstance also happens in the combination results, and the main reason may be the differences between *in situ* data and estimations. Because the climate station is far away from GANP station with some distances, the *in situ* observations are not the true snow depth data around the antenna and just as the reference. On the other hand, the period used to estimate snow-free reflector heights is the beginning of snow season and the assumed snow-free reflector heights are also not accurate, which will affect the results from the end of snow season. The correlation coefficient for SNR1 and SNR2 are 0.92 and 0.89 and the RMSEs are 0.07 and 0.09 m, respectively (see table I).

Fig. 4(c) and (d) shows the comparisons of snow depth estimations and *in situ* observations in 2012 snow season. The snow depth estimations from SNR1 and SNR2 are a little higher than *in situ* observations in snow period, while the trend is the same. The high deviation in snow period may also be due to the difference between *in situ* data and estimations. The correlation coefficient for SNR1 and SNR2 are both 0.92 and the RMSEs are 0.06 and 0.09 m (see Table I). Fig. 5 is the residual between GLONASS SNR estimations and *in situ* observations in 2012 and 2013 snow seasons, showing that most residuals are between –0.1 and 0.1 m. It is normal for some days with residuals of above 0.2 m.

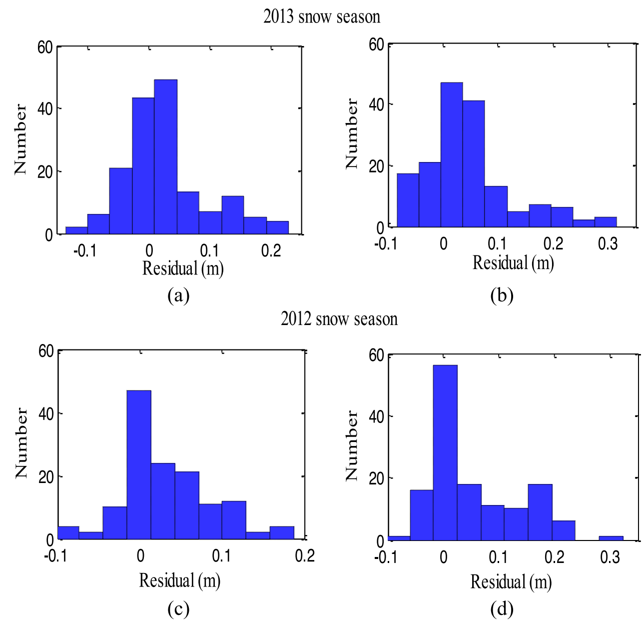

Fig. 5. Residuals between GLONASS SNR estimations and *in situ* observations in 2012 and 2013 snow seasons.

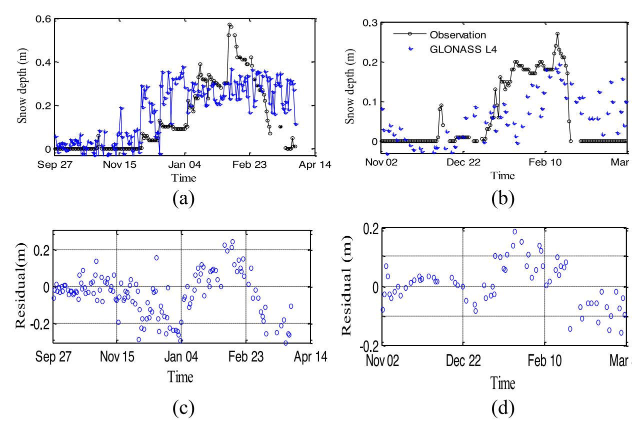

Fig. 6. Comparison of L4-estimated snow depth and *in situ* observations in 2013 and 2012 snow seasons, while (a) and (c) are in 2013, and (b) and (d) are in 2012.

B. L4 Results

Fig. 6(a) shows the comparison of L4-estimated snow depth with *in situ* observations in 2013 snow season. The snow depth estimations from L4 are not good, which have huge fluctuations. From Fig. 6(c), the residual is also a little big between 0.3 and –0.3 m. The correlation between estimations and *in situ* observations is 0.64 and RMSE is 0.13 m. Fig. 6(b) shows the comparison of L4 snow depth estimations with *in situ* observations in 2012 snow season. Because of the poor results, the number of estimations is less than SNR results. The correlation for 2012 snow season is 0.54 and the RMSE is 0.08 m.

From Table I, we can see the correlation and RMSE from GLONASS SNR and L4 results. The results from L4 method are worse than SNR. The reason may be that the L4 combination not only includes the multipath but also the other errors (ionospheric delays and noises), which will affect the results. Although the polynomial fitting can remove these effects, there are still some remained errors. During processing data, we also found L4 multipath pattern is easily affected by the high-frequency noises. When L4 multipath is converted into the Lomb–Scargle periodogram, there is always no domain frequency causing less estimation for most satellites. On the other hand, the Lomb–Scargle periodogram of L4 multipath has two peak heights shown in Fig. 2. It is difficult to know whether the highest peak height is for L1 or L2 with much noise, though L2 peak height is clearer than L1. The L4 combination is good for two carriers whose wavelengths are almost similar like GPS L2 and L5 signal. In this circumstance,

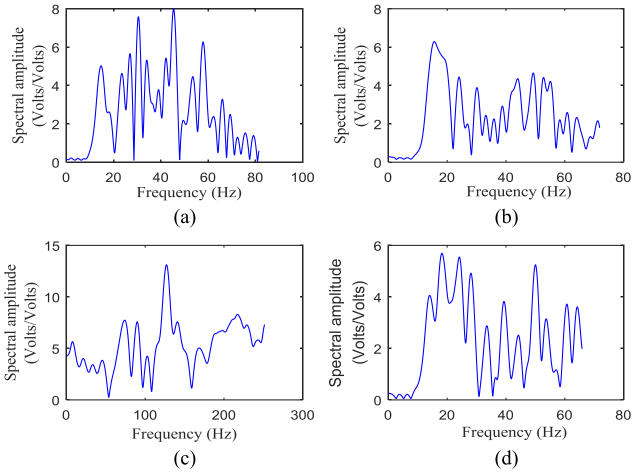

Fig. 7. Spectral periodogram obtained from free-ionosphere linear combination on November 2, 2012 for different satellites (a) PRN 3, (b) PRN 5, (c) PRN 11, and (d) PRN 19.

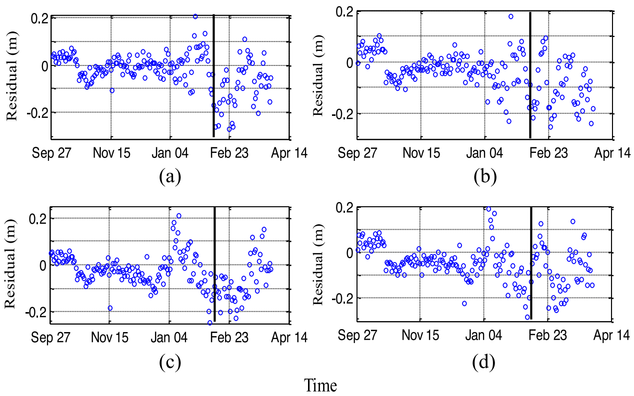

Fig. 8. Residuals between GPS and GLONASS SNR estimations in 2013 snow season (black line denotes snow peak time). (a) GPS SNR1 and GLONASS SNR1, b) GPS SNR1 and GLONASS SNR2, (c) GPS SNR2 and GLONASS SNR1, (d) GPS SNR2 and GLONASS SNR2.

the L4 combination only has one domain peak height. In order to detect the effect of ionospheric errors, free-ionosphere linear combination is also used to check whether ionosphere residuals will cause poor results. The formula of free-ionosphere linear combination is similar to (6) and cancels the ionospheric errors [12]. After obtaining the multipath errors, we evaluated the Lomb–Scargle Periodogram shown in Fig. 7. There is also no dominant peak for most satellites, meaning that ionospheric errors are not main reasons for poor results. It is probable that high-frequency noises have an impact on results. Therefore, more works are needed to improve the L4 method in the future.

V. Discussion

A. *Comparison of GPS and GLONASS*

In order to show the capability of GLONASS-reflectometry, GPS results are further compared. Snow depth estimations from GPS SNR data have a good correlation with *in situ* observations, while results from L4 are worse than SNR, which are the same with GLONASS. Fig. 8 shows the residual between GPS and GLONASS SNR estimations in 2013 snow season. Most residuals are small and absolute values are below 0.15 m. Fig. 9 shows the residual between GPS and GLONASS SNR estimations in 2012 snow season and Table II shows the comparison of results from GPS SNR1 and SNR2 with those from GLONASS SNR1 and SNR2. The correlation values in 2012 snow season are all above 0.90 and RMSE values are all below 0.1 m.

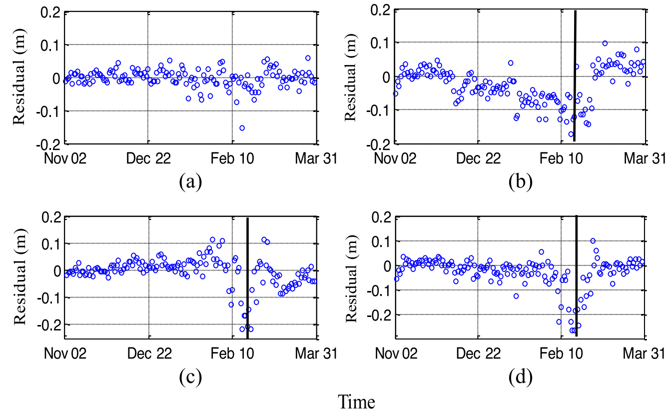

Fig. 9. Residuals between GPS SNR and GLONASS SNR estimations in 2012 snow season (black line denotes snow peak time). (a) GPS SNR1 and GLONASS SNR1, (b) GPS SNR1 and GLONASS SNR2, (c) GPS SNR2 and GLONASS SNR1, (d) GPS SNR2 and GLONASS SNR2.

TABLE II
Correlation and RMSE Estimations in 2012 Snow Season

GPS observation	GLONASS observation	Correlation coefficient	RMSE (m)
SNR1	SNR1	0.98	0.03
SNR1	SNR2	0.96	0.06
SNR2	SNR1	0.90	0.05
SNR2	SNR2	0.92	0.07

Through comparisons in 2013 and 2012 snow seasons, there is one common phenomenon for both snow seasons. The deviations between GLONASS and GPS estimations are small at the beginning of snow season, while they are becoming large with the increasing of snow depth, especially during the peak snow height period. The reason is that the snow depth is virtually zero during the beginning of snow season, and thus the reflector height estimated from snow free period is error free. On the other hand, the errors in the assumed ground height for snow free period will be produced when the snow variability increases with the increasing of snow depth. Also suddenly increasing or decreasing snow depth and wind will cause errors. Because of huge errors, deviations between GLONASS and GPS estimations will also become big with the increasing of snow depth.

Furthermore, multipath reflection points in Fig. 9 at GANP station for GPS and GLONASS are a little different. At the south part, areas covered by GPS and GLONASS tracks are almost same, while they are different at the north areas. Since there are no GPS tracks around the azimuth 360°, it will cause effects on results. The results in Table I are not all same between GPS and GLONASS and the main reason is that the areas covered by GPS and GLONASS tracks are different.

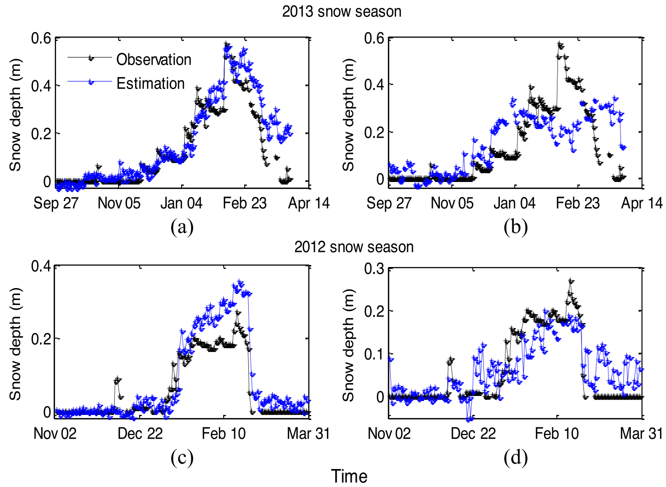

Fig. 10. Comparison of GPS and GLONASS combined estimations and *in situ* observations in 2013 and 2012 snow seasons. (a) SNR combination, (b) L4 combination, (c) SNR combination, and (d) L4 combination.

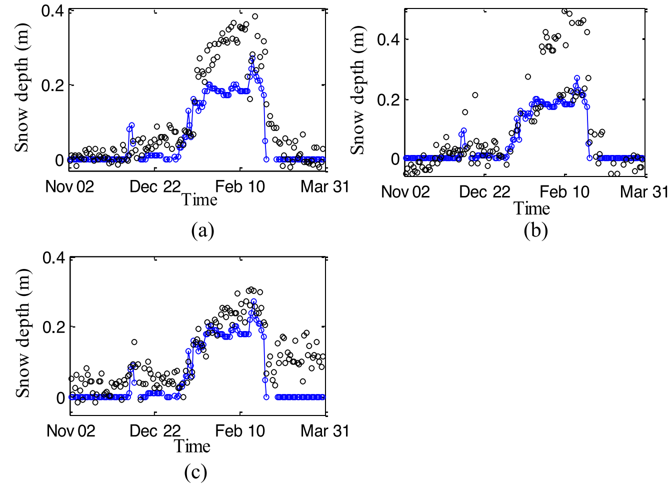

Fig. 11. Comparison of snow depth estimations from GLONASS SNR1 data with *in situ* observations at different azimuth zones in 2012 snow season. (a) NE, (b) SE, and (c) NW

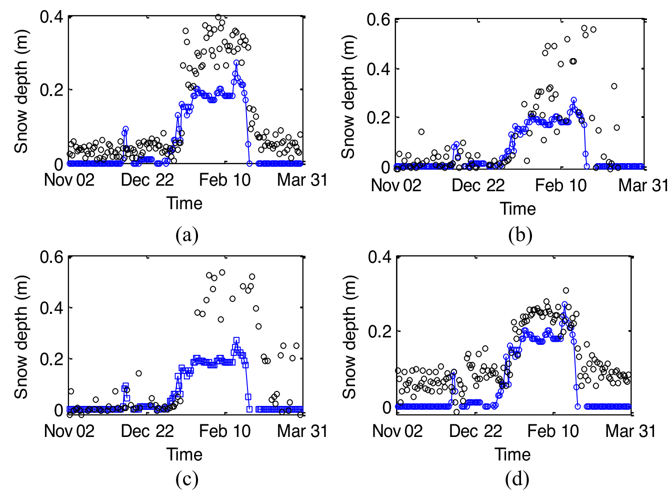

Fig. 12. Comparison of snow depth estimations from GPS SNR1 data with *in situ* observations at different azimuth zones in 2012 snow season. (a) NE, (b) SE, (c) SW, and (d) NW.

B. Combination of GPS and GLONASS

There are about nine visible GLONASS satellites every epoch at this station. If GPS visible satellites are included, there are about 20 satellites every epoch. The multipath reflection points at GANP station for GPS and GLONASS are nominal specular reflection points on the local horizontal plane surrounding the antenna and can be calculated by the Fresnel zones expressions. There will be more tracks if we combine the GPS and GLONASS observations. At the same time, there are also more reflection points on the ground, indicating that more sensing areas around the antenna are covered.

Fig. 10 shows the comparisons of combined GPS+GLONASS SNR and L4 estimations with *in situ* observations in 2013 and 2012 snow seasons. The snow depth estimations are much smoother with small fluctuations when compared to those only from GPS or GLONASS alone. Tables I shows the differences between results from combination of GPS and GLONASS and those from only GPS or GLONASS. For 2013 and 2012 snow seasons, the correlation and RMSE values for combined SNR and L4 estimations are a little better than most of the single system results, which means the results are improved partially after the combination, but not so significant. The reason is that the snow-free reflector heights obtained from summer data are more precise and near to true values. With more tracks every day, the sensing areas will cover more places around the antenna, meaning that snow-free reflector heights from different tracks of all satellites will also cover more areas. For many snow-free reflector heights, it is easy to detect the abnormal values. At the same time, there will be more estimations after converting reflector heights to snow depths in snow period for every day, which is helpful to detect the abnormal values too. On the other hand, the surface is not totally flat with some downhill and uphill bias. When all daily snow depth estimations are averaged, the average value will be much closer to the real snow depth with more estimations.

C. Effect of Azimuth Zones and Penetration

The above snow depth estimations are the average values of all azimuth zones, and we did not consider the effect of azimuth zones. Here, we analyze the differences for estimations from four azimuth zones according to the surrounding environment of GANP station. Some trees and one building at Southwest areas near GANP station are not good for the reflection, so the results from this area are very poor, even GLONASS without results (see Figs. 11 and 12). Because Southeast areas have some roads and constructions, results from this part are not good with smaller estimation. On the other hand, estimations from Northeast areas for GLONASS and GPS are both higher than *in situ* observations, while estimations from Northeast areas are normal, which can explain why estimations in 2012 snow season are higher than observations in Fig. 4. The reasons causing differences between azimuth zones are most due to the wind, surface tilting and relief, and all these factors will affect snow variability.

Besides the differences between azimuth zones, there is another effect, penetration, which should be considered. GPS and GLONASS signals both belong to L-band, so the signals will also penetrated into snow interiors besides reflections, meaning a few penetration distances in the snow. Although there are no obvious underestimations when compared to *in situ* observations, the underestimation percentage of the three algorithms (SNR, L4, and three-frequency combinations) is different. Also, a forward model of dry-snow has been developed to sense the substructure [17]. However, the multipath reflectometry is mostly used to sense wet-snow variations. Based on the forward model of dry-snow, penetration in multipath reflectometry should also be considered in the future.

VI. Summary

In this paper, snow depth variations are estimated from GLONASS-multipath reflectometry at one IGS station in Slovakia for two snow seasons. Results from GLONASS SNR have a good agreement with *in situ* observations, while L4 results are worse, which need more works to improve the L4 method in the future. Furthermore, we compare GPS and GLONASS results with the little differences. Therefore, GLONASS can estimate snow depth variations as good as GPS. While using combined GLONASS and GPS observations, the correlation and RMSE values for combined SNR and L4 estimations are better than results from the single system alone, but not so significant. Therefore, multi-GNSS combined observations are better used to estimate snow depth in the future because of high spatial resolution with more satellites.

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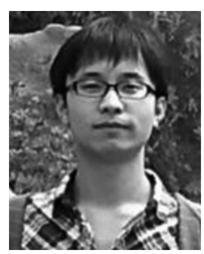

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