Assessing the operational applicability of automated measurements of snow water equivalent with low-cost GNSS receivers along a steep elevation gradient in the Eastern Swiss Alps

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Final report

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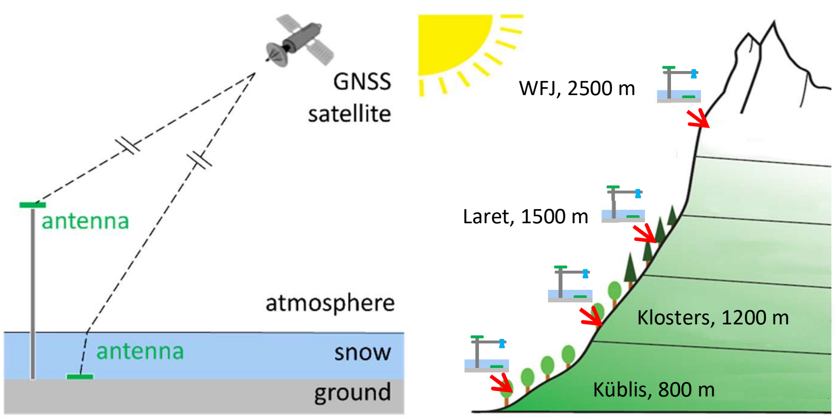

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1 Summary

The goal of the project is to evaluate the suitability of GNSS sensors for the operational measurement of snow water equivalent (SWE) in the Swiss Alps. Four observation sites along an elevation gradient in the Eastern Swiss Alps were selected and equipped with a GNSS-SWE measuring systems: Weissfluhjoch (2540 m a.s.l.), Laret (1515 m a.s.l.), Klosters (1200 m a.s.l.), and Küblis (815 m a.s.l.). In addition, manual and automatic reference data were collected at all observation sites. The Weissfluhjoch and Laret sites were already equipped with a comprehensive set of automatic sensors including automated snow load (SWE) sensors. At the observation sites in Klosters and Küblis additional snow height sensors and cameras were installed. Manual snow profiles (including total SWE, stratigraphy, density, liquid water content) were performed bi-weekly at the Weissfluhjoch and weekly at the other sites.

The GNSS snow algorithm was improved by adding the GALILEO signals to the GPS signals already used into the preliminary evaluation. In this way more satellite signals are available and the SWE derivation precision increases.

The first measurement season was characterized by large amount of snowfall and for this reason by several large data gaps in the GNSS-SWE data. The unexpected large snow load caused the failure of the mast of the stations in Klosters and Küblis and consequently the movement of the reference antenna. Since, the derivation of SWE based on the difference of the GNSS signal measured by the antenna above and below the snow requires the relative distance of the antennas to be precisely known and constant over the entire season, part of the data cannot be evaluated. A further issue was that for Laret a problem with the data storage caused the loss of data after the 16 April 2019. Moreover, we had frequent short interruptions of the data logging for Laret, Klosters and Küblis that required an improvement of the GNSS system firmware in summer 2019. The second season was more successful. Thanks to an improved mechanical setup and data acquisition software together with a closer monitoring of the GNSS data collection the occasional data loss was much less severe than in the previous winter. The Küblis site had just few snowfalls followed by mild weather. For this reason and due to the data gap of the previous season the data set from Küblis allows for a qualitative evaluation only.

The comparison to the manually collected SWE data indicate that the GNSS-based SWE estimation is very robust and has very good accuracy with an overall root mean square error (RMSE) of 33 mm and a root mean square relative error (RMSRE) of 12 %. The accuracy was comparable for dry-snow and wet-snow conditions with no particular dependency on elevation. The comparison of GNSS-derived values of SWE with the results of the other automatic measurement methods for SWE (snow scale and pillow) shows a similar performance when snowpack is dry. Once the snowpack is wet, the GNSS data are closer to the reference data since both snow scale and pillow exhibit anomalous variations of SWE at the beginning of the melting season. Noise in GNSS-SWE signal prevents reliable estimation of new snow water equivalent during snowfalls. Only large events are reliably detected, however with rather poor precision. The GNSS method in its present form cannot be applied for estimation of daily precipitation. However, the same conclusion can be drawn for all other automated SWE measurement methods.

Moreover, we used two snow models to estimate SWE at the measuring sites: the physically based model SNOWPACK and a somewhat less sophisticated model of the Operational Snow Hydrological Service (OSHD) at SLF that estimates SWE from snow depth. The accuracy of the OSHD model was as good as the accuracy of the GNSS method. On the other hand, the accuracy of the SNOWPACK model was less accurate, in particular it largely overestimated SWE during the second season 2019-2020.

2 Scientific report

2.1 Introduction

Snow water equivalent (SWE) is a key property of the seasonal snow cover as the water stored in the snowpack is a crucial contribution to the hydrological cycle in mountainous areas – and of vital importance for the well-being of people downstream of mountain catchments, e.g. on the Indian subcontinent. In general, snow is an important element of the climate system due to its high reflectivity, cooling effect and insulating properties – in short, an essential climate variable (ECV). Monitoring spatial distribution and temporal evolution of snow mass is hence essential for assessing snow storage and subsequent runoff. Moreover, melting snow may contribute to flooding.

While considerable progress has been made with large scale modeling and remote sensing of SWE, direct measurements of SWE are still essential, but are scarce and mostly non-continuous. Traditional networks are typically based on weighing a known volume of snow. Occasionally, scales (or so-called snow pillows) are used, which do provide continuous data, but are rather expensive and often plagued with inherent accuracy problems due to bridging effects (Johnson et al., 2015).

The GNSS method, we investigated, derives SWE from the difference in signal strength and phase measured above and below the snow cover with low cost sensors allowing the automatic measurement of SWE at high temporal resolutions and reasonable costs. The GNSS-SWE derivation algorithm relies on snow density and liquid water content (LWC) models and calibration. However, these snow properties can vary considerably with climatic conditions and elevation. Hence, the goal of the project is to evaluate the suitability of GNSS sensors for the operational measurement of snow water equivalent (SWE) in the Swiss Alps, in particular at different elevations, and further develop the GNSS snow measurement technique to improve its performance so that it becomes applicable for different conditions. To this end, four stations with GNSS receivers were installed and operated over two winter seasons along a steep elevation gradient from Küblis (815 m a.s.l.) to Weissfluhjoch (2540 m a.s.l.) and validation data were collected. We further compared the GNSS-based SWE estimates to results of numerical models for SWE estimation. This project relates to column 1, priority 1.3 of the GCOS Switzerland Strategy 2017-2026, that aims at fostering existing and new measurement methods.

2.2 Methods and activities

2.2.1 GNSS measuring principles

The low-cost GNSS system consists of two antennas and one receiver. One antenna is placed on the ground and gets covered by snow in the late fall and the second antenna is mounted on a pole and remains above the snow cover for the entire winter. The snow on the ground influences the GNSS signal received by the first antenna, whereas the atmospheric conditions influence the signal of both antennas. By computing the difference in GNSS signal characteristics between the two antennas it is possible to separate the effects of the snow from the atmospheric effects on the GNSS signal and thus derive the snow cover properties. Deriving snowpack properties is based on the GNSS signal in the microwave L-Band with a central frequency of 1575.42 MHz (wavelength ca. 19 cm) of both GPS and Galileo. Travelling through snow the GNSS electromagnetic waves are affected by time delay, attenuation, refraction, and reflection. Time delay and attenuation for dry snow depends mainly on the snow density, whereas if water is present in the snow the signal speed deceases and signal attenuation significantly increases with increasing LWC. Hence, different algorithms to derive SWE need to be employed for dry-snow and wet-snow conditions. For dry snow, SWE is determined solely from the phase carrier time delay and snow depth (HS) is derived from SWE with a simple densification model, where a new snow layer densifies in time exponentially from an initial density (100 kg m^{-3}) up to a maximum density (357 kg m^{-3}) with the characteristic densification time $\tau = 6$ days. For wet-snow conditions, the processing is more complex and based on both phase delay and signal attenuation. For more details on the GNSS algorithm see Koch et al. (2019) and Henkel et al. (2018).

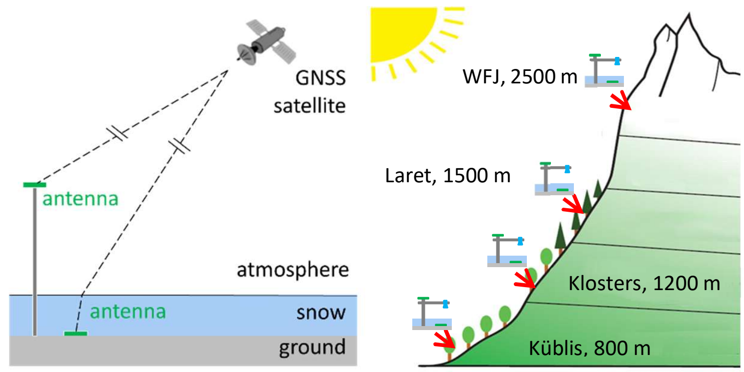

Figure 1: Schematic representation of the GNSS system to derive SWE (left) and the test sites along the elevation gradient (right).

2.2.2 Study sites

At the four study sites covering a steep elevation gradient form 2540 m a.s.l. to 820 m a.s.l the snowpack can be considered as representative or the respective elevation (Figure 1) in the given climate region. Each site is equipped with automated snow and weather sensors. At Weissfluhjoch (2540 m a.s.l, 46°49'47'' N, 9°48'34''E) SWE is measured automatically with a snow scale and a snow pillow, snow depth with ultrasonic sensors. Additionally, snow depth, new snow height, and water equivalent of snowfall (HNW) is measured daily at 8:00 by an observer. The site of Laret is at 1510 m a.s.l. (46°50'2''N, 9°52'17''E) and is also equipped with automated sensors. SWE is measured continuously with a snow scale, snow depth with an ultrasonic and two laser sensors and precipitation with heated weighing gauge. The Klosters site (1210 m a.s.l., 46°51'49''N, 9°53'17''E) is located near the present location of the long time SWE measurement series. A continuous and automated laser snow depth sensor was installed in the immediate vicinity of the GNSS ground antenna. Snow depth, new snow height (HN), and water equivalent of snowfall (above 10 cm HN) are measured daily. An automatic pluviometer is present within 200 m at the same elevation (46°51'54"N, 9°53'22"E). The Küblis site is at 820 m a.s.l. (46°54'48''N, 9°46'54''E) near the MeteoSwiss snow measurement site. Snow depth was measured continuously by a laser sensor. The snow depth, new snow height, and precipitation from a rain gauge were measured manually daily. For the winter 2019-2020 the manual measurement field (MeteoSwiss) was moved to a nearby location (distance 330 m, elevation difference 20 m). Camera pictures documenting snow conditions and if snow was covering the ground antenna, are available for all sites.

2.2.3 Models

We used two different models for a point derivation of SWE: the physically-based numerical snow cover model SNOWPACK and a less sophisticated model used by the Operational Snow Hydrological Service (OSHD) at SLF.

The OSHD model estimates SWE from snow depth using a snow density model describing accumulation and densification of the snowpack layer by layer. The model is based on an approach originally presented by Martinec and Rango (1991). The OSHD model is a recalibrated version of their original model using data from over 10,000 snow profiles as described in Jonas et al. (2009).

SNOWPACK simulates the development of the complete snowpack (snow layering and microstructure) during the winter based on meteorological input data. The model solves both mass and energy balance between snow, atmosphere and soil. Hence, it requires a large number of meteorological input parameters such as air temperature, relative humidity, wind, incoming/reflected short wave, incoming long wave radiation or surface temperature, precipitation and/or snow depth, ground temperature or geothermal heat flux. The input parameters are either measured at a meteorological station at the point of the simulation or are interpolated from nearby stations. In the present study, we used the operational setup, where the measured snow depth is used as input to estimate the amount of new snow.

2.2.4 Activities

The main activities followed the six work packages as planned:

WP 1: Selection of observation sites and installation

In the fall 2018, four observation sites were selected and equipped with a GNSS-SWE measuring systems: Weissfluhjoch (2540 m a.s.l.), Laret (1515 m a.s.l.), Klosters (1200 m a.s.l.), and Küblis (815 m a.s.l.). At the observation sites in Klosters and Küblis additional snow height sensors and cameras were installed.

The setup of stations in Klosters and Küblis was improved in the fall 2019. Unfortunately, the large amount of snow during winter 2018-2019 caused the failure of the mast of the stations in Klosters and Küblis and consequently the movement of the reference antenna. The derivation of SWE from the difference of the GNSS signal measured by the antenna above and below the snow requires the relative distance of the antennas to be precisely known and constant over the entire season. Hence, the data for parts of the season 2018-2019 could not be analyzed. For this reason, we used more robust poles in the second winter to ensure that the reference antenna did not move due to heavy snow load. Additionally, we installed air temperature sensors with the purpose of using the air temperature data for the snow cover modelling.

WP 2: Collection of validation data (and continuous GNSS measurements)

Manual snow profiles were performed weekly for the sites of Laret, Klosters and Küblis and bi-weekly at the Weissfluhjoch site. The measurements included snow depth, SWE and snow temperature. The liquid water content (LWC) was derived from snow density (from snow cutter) and relative dielectric permittivity (capacitive sensor; Denoth, 1994). LWC was measured only for some of the manual profiles due to the time-consuming procedure and the need for a trained observer.

WP 3: Extension and adaptation of GNSS snow algorithm

The GNSS snow algorithm was improved by integrating the GALILEO signals into the evaluation (Lamm et al., 2018).

The GNSS system firmware was improved since during the winter 2018-2019 we had frequent interruptions of the data logging and therefore GNSS-derived SWE data were available at irregular times. Thanks to the improvements of data acquisition software together with a closer monitoring of the GNSS data collection the occasional data loss was much less severe than in the first winter. We had two data gaps of a few weeks for Laret due to electronic problems at the data logger.

The planned integration of a more sophisticated snow model (aging and densification) in the GNSS algorithm was considered of secondary importance due to the already well working GNSS-SWE estimation. The dataset collected in this study constitutes an excellent base for a future improvement of the density model.
A preliminary study on the use of only one GNSS receiver and a Virtual Reference Station for determining SWE has been performed by our project partner by Patrick Henkel at AnaVs using the data of the station in Laret (see outreach chapter).

WP 4: Data analyses and comparison to validation data

The collected GNSS and reference SWE data have been analyzed and compared. The main results and conclusions are presented below.

WP 5: Comparison to modelling data

The GNSS derived SWE was compared to SWE from two different snow models. Below we present an evaluation of the accuracy of modeled and GNSS-derived SWE relative to the reference of manual SWE.

WP 6: Recommendation on operational use

Based on the results of the comparisons in WPs 4 and 5 we make recommendations for further research as well as on the suitability of GNSS-derived SWE for operational use within the present SWE observation network in Switzerland.

2.3 Results

2.3.1 SWE

The seasonal evolution of the GNSS-derived SWE (temporal resolution ca. 12 h) and the reference data for the four measuring sites along the elevation gradient are shown in Figure 2. The GNSS-derived SWE was in good agreement with the reference data during both winter seasons for the three higher elevation sites. For the measuring site Küblis only a qualitative evaluation is possible as there was hardly any snow during winter 2019-2020 and a data gap in winter 2018-2019. However, the available data from Küblis show that the GNSS system can discern very well if snow is laying on the ground also for a total amount of SWE lower than 10 mm. The GNSS-derived SWE agreed generally well with the manual SWE data for the entire course of the season, whereas the snow scale and pillow at Weissfluhjoch and Laret at the onset of the melting period presented anomalous variations such as sudden decreases in SWE (May 2019 and end of April at WFJ, mid March 2020 at Laret) and daily cycles (Laret, end of March 2020). For this reason, we evaluated the accuracy of the GNSS-derived SWE relative to the manual SWE measurements. Scattering, root mean absolute and relative errors, and linear regression lines with corresponding parameters are shown in Figure 3. With a shallow snowpack the relative spatial variability can be very large compared to the total amount of snow. In such cases, the difference between SWE above the GNSS antenna and at the manual measuring location can be considerably large, and the relative error very high. Therefore, we considered just the cases with SWE > 25 mm. For the data from all measuring sites the root mean square error (RMSE) was 33 mm and the root mean square relative error (RMSRE) was 12 %. The absolute error increased with elevation, whereas the relative error decreased, since at higher elevation sites snow depth was generally larger. Both RMSE and RMSRE for the snow scale and pillow were significantly higher compared to the GNSS-derived SWE (Table 1). The bad accuracy of SWE from snow scale and pillow is mainly due to the large differences observed at the onset of the melting period for the snow pillow and scale (Figure 2).

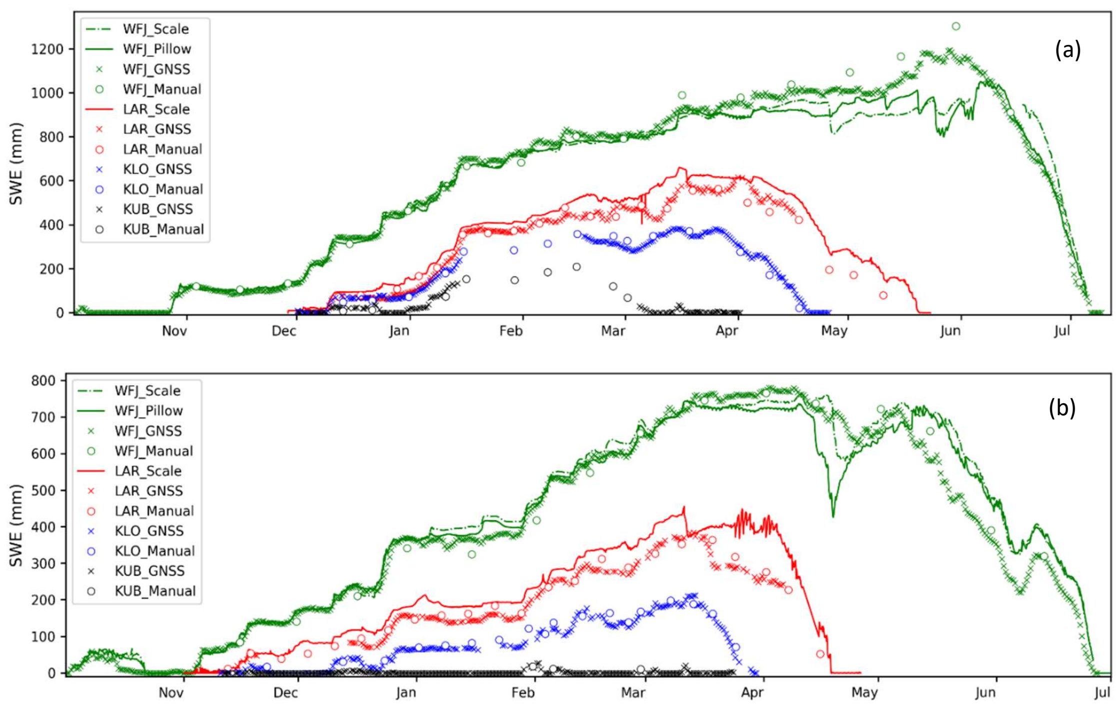

Figure 2: GNSS-derived SWE and reference data for (a) the winter 2018-2019 and (b) 2019-2020 for the stations at Weissfluhjoch 2540 m a.s.l. (WFJ), Laret 1510 m a.s.l. (LAR), Klosters 1185 m a.s.l. (KLO), and Küblis 820 m a.s.l. (KUB).

We analysed the accuracy of the GNSS-derived SWE separately for dry-snow and wet-snow conditions. The separation between dry-snow and wet-snow conditions was based on the GNSS-derived LWC, which is derived from the GNSS signal strength at the ground antenna. The accuracy of GNSS-derived SWE was very good for both wet-snow and dry-snow conditions. (Figure 3 and Table 1). In general, the absolute error was larger for wet-snow conditions, whereas the relative error was lower. Also, in this case the difference was mainly due to the generally heavier snowpack late in the season ($\text{mean}(SWE_{\text{wet}}) =$ 440 mm and $\text{mean}(SWE_{\text{dry}}) =$ 300 mm).

Table 1: Root mean square error (RMSE), root mean square relative error (RMSRE), number of data points N, and linear regression parameters (slope, intercept, and R²) for SWE determined with snow pillow and scale compared to the manual measurements for the single stations and all data. For the snow pillow the data from Weissfluhjoch (WFJ) were used. For the snow scale the analysis was done with data from WFJ and Laret.

	RMSE (mm)	RMSRE (%)	N (-)	slope (-)	intercept (mm)	R^2 (-)
Pillow	92	13	32	0.81	88	0.98
dry	47	11	18	0.90	45	0.99
wet	128	15	14	0.68	186	0.95
Scale	79	17	61	0.83	83	0.97
dry	39	14	37	0.92	40	0.99
wet	117	20	24	0.65	209	0.96

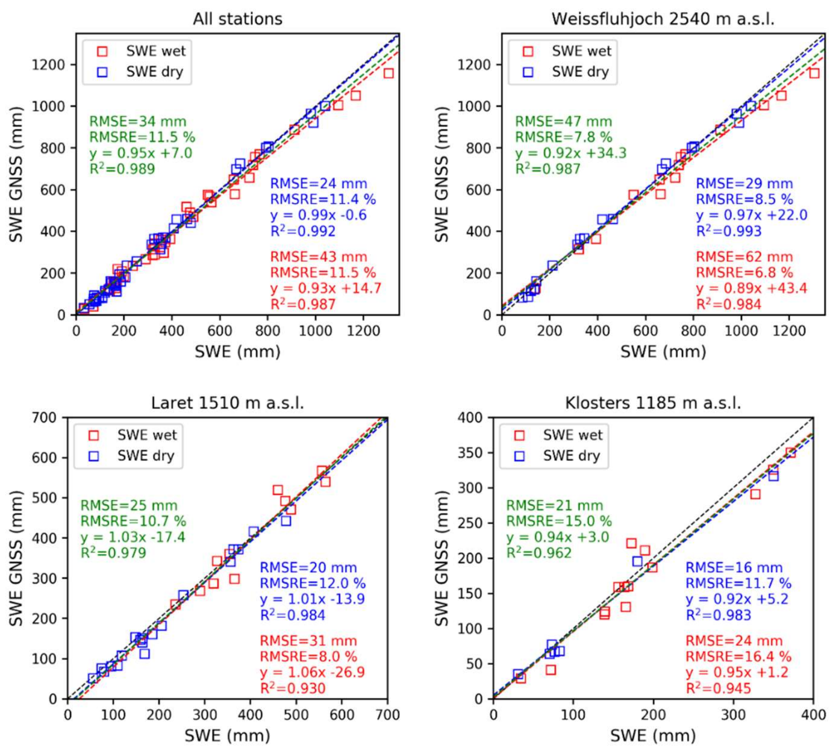

Figure 3: Scatter plot of GNSS derived SWE vs. SWE from manual measurement for dry-snow conditions (blue) and wet-snow conditions (red) for all sites together and the single sites. We do not show the data for Küblis because only few data points were available. The dashed lines represent the linear regressions (green for all data). Data points with less than 25 mm SWE were excluded from the analysis. The 1:1 line is shown in black.

2.3.2 New snow water equivalent

Some operational applications (e.g. avalanche prevention, flood prediction, …) require not only an estimation of SWE of the snowpack but also the daily variations indicative of snowfall and melting. Therefore, we evaluated if the GNSS system can reliably measure such variations over 24 h and 72 h in GNSS-derived SWE by comparing them with reference precipitation data. As reference data for the WFJ we used the new snow water equivalent measured manually daily at 8 a.m. For the other sites, which are less influenced by snow drift due to wind, we use the precipitation data from nearby pluviometers (automated for Klosters and Laret, and manual for Küblis). For this analysis, we used only the data from the season 2019-2020, since the GNSS-derived SWE for Laret, Küblis und Klosters for the season 2018-2019 was available only at irregular time intervals and determining the daily change in SWE (ΔSWE) was not feasible.

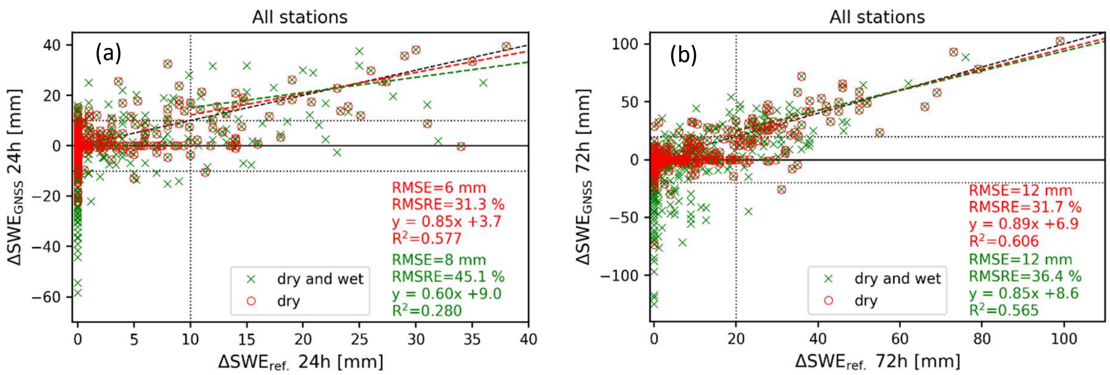

Figure 4: Scatter plot of changes in GNSS-derived SWE vs. new snow water equivalent from reference measurements (pluviometer or observer) for all stations (winter 2019-2020), changes (a) over 24 h (b) over 72 h. The dashed lines indicate a linear regression for the dry snow cover case (red) and the entire season (green). The black line indicates the 1:1 line. The linear regression was computed only for the data points larger than 10 mm for a 24 h period or 20 mm 72 h period (dotted lines).

Snow melt results in a decrease in total SWE and consequently in a negative $\Delta SWE_{\mathrm{GNSS}}$ which is not measured with the reference method. Therefore, we did a separate analysis for the dry-snow conditions. Figure 4 shows a scatter plots of ΔSWE over 24 h and 72 h from the GNSS vs. the reference data for all sites for winter 2019-2020. The scatter of the daily GNSS-derived values of ΔSWE relative to reference data is quite large. Even for days without precipitation the fluctuations in the total SWE can be quite large as can be seen in Figure 5 showing the histograms of ΔSWE for GNSS, pillow, and scale for the days with precipitation water equivalent HNW< 3 mm. For dry-snow conditions the majority of the false precipitation events have a magnitude lower than 10 mm over 24 h and 20 mm over 72 h. Therefore, we defined a threshold of 10 mm over 24 h and 20 mm over 72 h to determine whether on a given day there was an increase, decrease or no change in total SWE and HNW. The contingency table (Table 2) compares the number of days with or without precipitation in the reference data with the number of days with an increase, decrease or unchanged value of SWE. About 10% of days without consistent precipitation and dry-snow conditions resulted in a false alarm in $\Delta SWE_{\mathrm{24h}}$ (increase or decrease). From the days with HNW > 10 mm about 35% had a $\Delta SWE_{\mathrm{24h}}$ < 10 mm. The RMSRE for the correctly detected precipitation events was 31% (linear regression in Figure 4a). Missed events or false alarms had a daily variation of SWE up to 35 mm. For the 3-day sum of new snow, there were fewer false event days without precipitation, but again about one third of the precipitation days with HNW_{72h} > 20 mm were not detected; the RMSRE for the precipitation days was 32%. The maximum magnitude of the undetected/false events over 72 h was 35 mm water equivalent. If the dry-snow conditions are included in the analysis the accuracy of ΔSWE decreases compared to dry-snow conditions only, with an increase in false and missed precipitation days. Figure 5 shows that the increase in false events is strongly influenced by melting (shift of the histogram to the negative values). The scatter of $\Delta SWE_{\mathrm{24h}}$ is higher when wet-snow conditions are included (RMSRE = 45 %, and lower correlation). The accuracy for large precipitation events ($\Delta SWE_{\mathrm{72h}}$) is similar for dry-snow and wet-snow conditions.

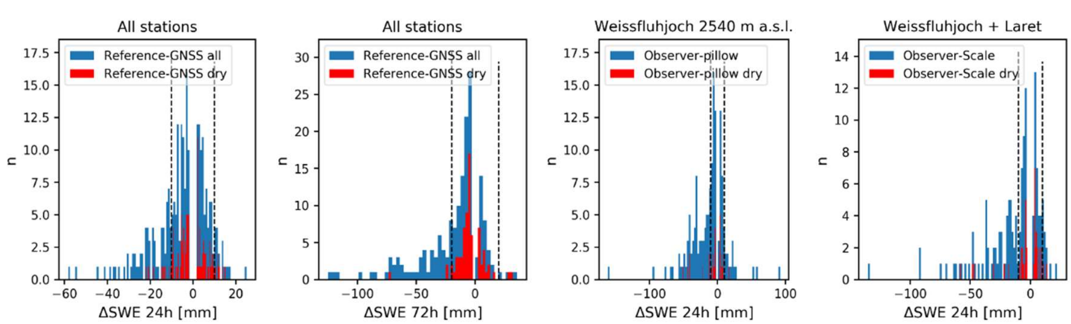

Figure 5: Histogram of $\boldsymbol{\Delta SWE_{GNSS}}$ *for the cases where the reference HNW was < 3 mm for 24 h (A), and for 72 h (B) for all stations and winter 2019-20. In (C and D) histogram of* $\boldsymbol{\Delta}$*SWE of the snow pillow (C) and snow scale (D) over 24 h for the cases were the reference HNW was < 3 mm. Data from Weissfluhjoch and Laret for both winters.*

Table 2: Contingency table illustrating the detection performance of new snow events for GNSS (all sites, winter 2019-2020), snow pillow (WFJ, 2018-19 and 2019-20) and snow scale (WFJ and Laret, 2018-19 and 2019-20). We considered new snow days with a SWE increase larger than 10 mm in the preceding 24 h or larger than 20 mm in the preceding 72 h. The same threshold was used for the decrease. The first number refers to dry-snow conditions only. The second to both dry-snow and wet-snow conditions combined. N is the total number of days we considered.

	ΔSWE 24 h		**ΔSWE 72 h**	
	Ref. Yes	**Ref. No**	**Ref. Yes**	**Ref. No**
GNSS no	15/34	289/435	21/42	267/396
GNSS increase	25/44	19/44	45/79	9/26
GNSS decrease	1/1	9/75	1/2	3/71
N	361/636		346/616	
Pillow no	6/7	245/358	9/17	205/289
Pillow increase	47/68	10/30	76/106	4/21
Pillow decrease	0/2	7/68	0/3	10/79
N	321/539		306/517	
Scale no	11/15	336/543	11/28	269/440
Scale increase	64/94	14/36	106/149	19/44
Scale decrease	0/2	8/75	0/5	10/80
N	439/777		420/751	

We did not find any significant difference in the accuracy of ΔSWE between the sites at the different elevations. Compared to the GNSS-derived value the number of missed/false events for dry-snow conditions was much lower for the snow pillow and lower for the snow scale (Table 2). However, the large underestimation in SWE of pillow and scale occurring at the onset of the melting season (see Figure 2) caused large errors in ΔSWE.

2.3.3 Comparison to numerical models

We evaluated the accuracy of modeled and GNSS-derived SWE relative to the manual SWE data. Figure 6 shows the evolution over the two winters of modelled and GNSS-derived SWE. The OSHD model deriving SWE from measured HS only was applied for all stations, whereas the SNOWPACK model data are only available for Laret. Figure 7 shows scatter plots of GNSS-derived and modeled SWE against manual SWE with respective linear regressions, RMSE and RMSRE. Both seasonal development and scatter plots indicate a similar accuracy of GNSS and OSHD model. With a RMSE of 30 mm and 34 mm and RMSRE of 12.3% and 11.5 % for OSHD model and GNSS respectively. There was a tendency toward overestimation by the OSHD model, in particular for the lower elevation sites. The results were similar for both seasons.

The Snowpack model showed a lower accuracy with RMSE = 65 mm and RMSRE = 19.7%. Whereas the SWE estimation for the seasom 2018-2019 was fairly good, SNOWPACK largely overestimated the SWE for the season 2019-2020. The main weakness of SNOWPACK in this context is its complexity, which requires a complete set of meteorological input data and according supervision and data curation.

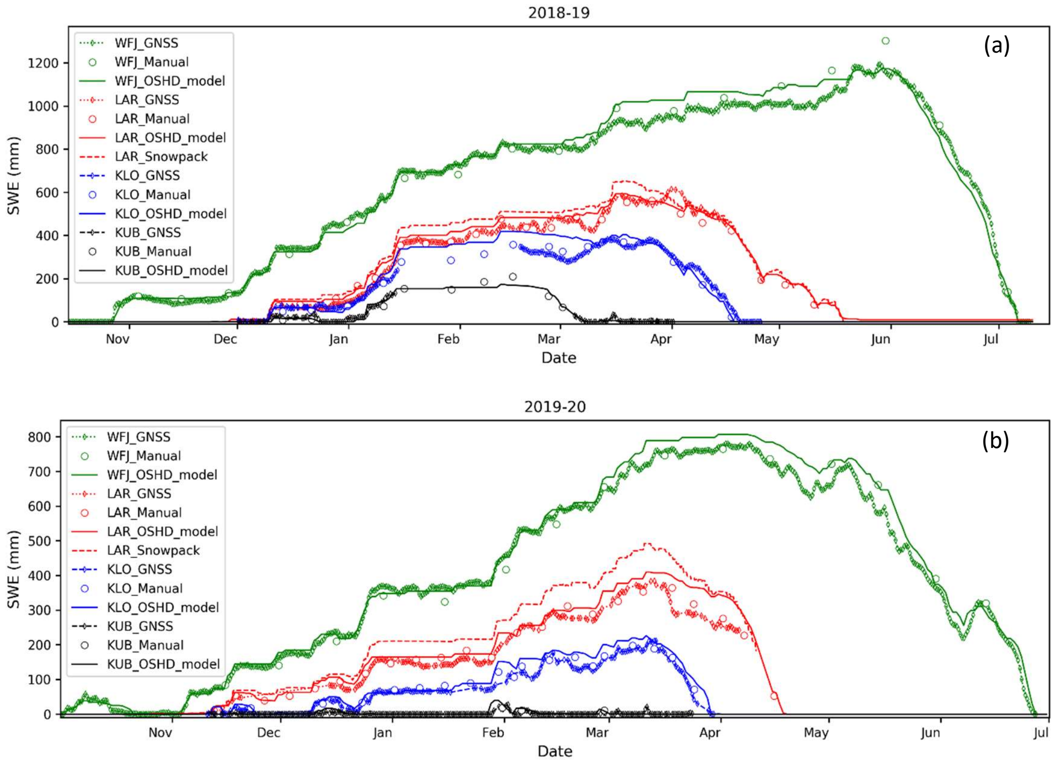

Figure 6: Comparison of measured and modeled SWE for the winter (a) 2018-2019 and (b) 2019-2020 for the stations at Weissfluhjoch 2540 m a.s.l. (WFJ), Laret 1510 m a.s.l. (LAR), Klosters 1185 m a.s.l. (KLO), and Küblis 820 m a.s.l. (KUB).

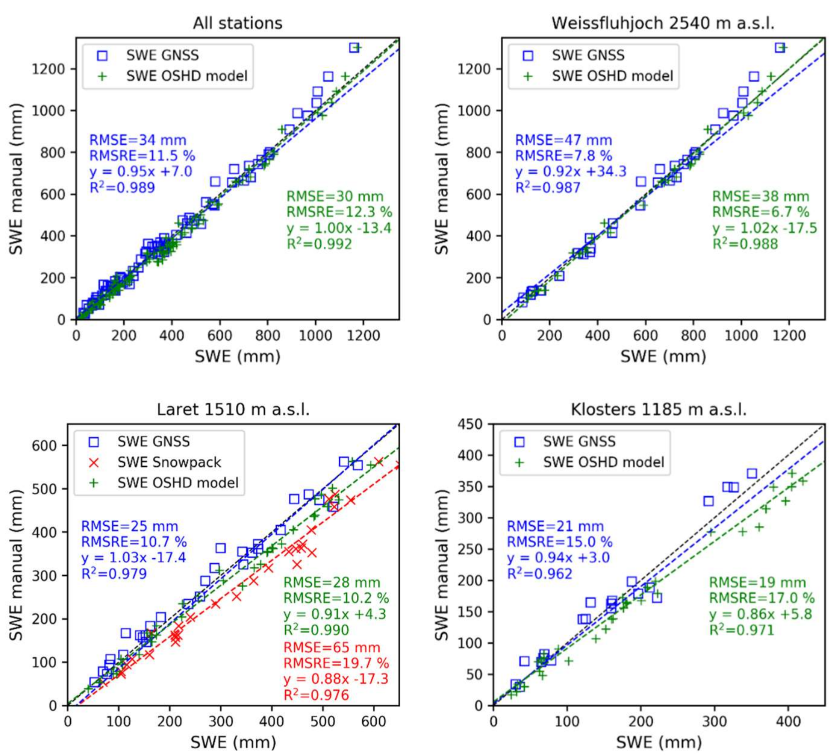

Figure 7: Scatter plot of GNSS-derived and modeled SWE vs. SWE from manual measurement for all sites together and the single sites. We do not show the data for Küblis because only few the data points were available. The dashed lines represent the linear regressions. Data points with less than 25 mm SWE were excluded from the analysis. The 1:1 line is shown in black.

2.4 Recommendations for operational use

Our analysis confirmed that the GNSS system can reliably measure SWE at the different elevations where different snow conditions prevail. Hence, we consider the GNSS method as suitable for operational SWE monitoring. The GNSS method represents to our knowledge the best and cost-effective way for measuring SWE and LWC simultaneously, continuously and non-destructively.

The SWE derivation from GNSS signal differences is very sensitive to relative movements of antennas. Therefore, it is crucial that the reference antenna is mounted on a stable structure or pole. This should generally not be a problem at existing automatic stations such as the ones of the MeteoSwiss or SLF network. For new or so far manual stations, it is recommended to mount the reference antenna on an existing structure or to a massive pole well anchored to the ground.

Although the results we obtained are accurate and quite robust, the employed measuring system provided by ANAVS is in a pre-operational stage and quite prone to errors resulting in data gaps. For a widespread operational use, the measuring system must become more reliable and robust. In our opinion, these improvements can be achieved but requires some time and effort by the company.

A further issue is the data processing. At the moment, only a light version of the data processing is done on the station and the data require post-processing to obtain good accuracy. This issue should be solved, since near-real time availability of the data as well as monitoring of the data quality are an absolute prerequisite for operational use of the GNSS system for SWE monitoring.

At present, the SWE data are available only at 12 h time resolution, because the GNSS algorithm needs a certain time window (at least 8 h) for reaching good values. For operational applications a higher data frequency would be highly benefical. The use of multi-frequency GNSS signals should improve the data frequency without losing accuracy. See outlook for more details.

2.5 Conclusions

The GNSS-based SWE estimation is robust and accurate, with no particular dependency on elevation or snow conditions. The accuracy was found to be similar for dry-snow and wet-snow conditions and there was no large influence from rain-on-snow events. Based on manual reference measurements, RMSE was 34 mm and RMSRE 11.5%. For low snow mass the relative error increased exponentially, and therefore for SWE below 10 mm just a qualitative estimation was possible. However, the GNSS-method determined reliably whether snow was lying on the ground. This accuracy is achieved for a GNSS data frequency of 12 h. The accuracy of GNSS-derived SWE was similar to the measurements of snow scale and pillow for dry-snow conditions and better for wet-snow conditions. Our analysis indicated that noise in the GNSS-SWE signal prevents a reliable estimation of the water equivalent of new snow. Only large snowfall events are reliably detected, however with poor precision in magnitude estimation. Snow scale and pillow showed similar results. All methods evaluated are therefore not suitable for estimating water equivalent of new snow.

We conclude that the GNSS-based derivation of SWE is a valuable, affordable, and reliable alternative to manual measurement or other automated SWE sensors; the method is in principle suited for operational SWE monitoring.

The OSHD model deriving SWE from measured snow height produced similarly good results as the GNSS method. For similar models see e.g. Winkler et al. (2020) or Hill et al. (2019). Such models rely on HS only as input and on calibration of density and densification based on previous data. With a densification model as included in the OSHD model very good SWE estimates (similar to the GNSS-derived SWE) can be obtained by using only a HS as input. Since automated measurements of HS are well ethablished and already available at many locations, such a densification model can be considered a valid aternative. Otherwise, modelling SWE has also disadvantages compared to direct measurements. Since the densification models are calibrated with past data, an unknown bias may exist at certain locations or if prevalent snow properties change over time (in particularly density). The tendency toward overestimation of SWE at the lower locations may be due to such a calibration bias. An increasing number of rain-on-snow events may be a further problem. These issues may be a considerable problem for long-term time series in the context of climate monitoring. The algorithm for the GNSS-based SWE derivation is also based on densification model used for estimating the internal parameter HS. However, errors in estimating HS have only a marginal influence on SWE estimates. The GNSS method would be less affected by long-term changes in snow density, and therefore seems more suited for long-term automated SWE monitoring.

We consider the tasks planned for the last two years as largely completed all milestones were completed; all milestones according to the project plan were reached.

2.6 Outreach

The GNSS measurement method for SWE was featured in the WSL magazine DIAGONAL 1/19 (page 33).
https://www.wsl.ch/fileadmin/user_upload/WSL/Publikationen/DIAGONAL-WSL-Magazin/19-1-Biodiversitaet/WSL_Diagonal_19_1_de_web.pdf

First results from the winter 2018-2019 were presented at European Geoscience Union (EGU) conference in Vienna in May 2019.
https://meetingorganizer.copernicus.org/EGU2019/EGU2019-15715.pdf

Results of the validation study with the data of the two winters 2018-2019 and 2019-2020 (Figure 2) were presented at European Geoscience Union (EGU) conference in May 2020. At the link below, also the presentation can be downloaded.
https://meetingorganizer.copernicus.org/EGU2020/EGU2020-17824.html

A preliminary study on the use of only one GNSS receiver and a Virtual Reference Station for determining SWE based on data of the station in Laret was presented at European Geoscience Union (EGU) conference in May 2020. This approach is very promising since it would allow a station setup that might also be suited for slopes.
https://meetingorganizer.copernicus.org/EGU2020/EGU2020-20935.html

The main results of the study will be presented in form of an interactive poster at the American Geophysical Union (AGU) Fall Meeting in December 2020.
https://agu.confex.com/agu/fm20/meetingapp.cgi/Paper/725143

2.7 Publication of data and results

All essential project data are available on the WSL data portal ENVIDAT.
https://www.envidat.ch/dataset/swe-measurements-gnss-along-a-steep-elevation-gradient
doi:10.16904/envidat.186

A paper describing the results of the study is in preparation and will be submitted to a peer-reviewed journal very soon. The publication will contain a more comprehensive analysis of not only the GNSS-derived SWE but also the GNSS-derived LWC and HS.

2.8 Outlook

Given the positive outcome of the project we are committed to continue the development of the GNSS method and will explore new possibilities of application.

Since snow cover properties are measured with the GNSS method non-invasively from below the snow cower, the method can be deployed in avalanche terrain without the risk of being damaged by avalanches. The possibility of measuring LWC is very interesting for studying wet-snow and glide-snow avalanches. For the next winter, we will install the infrastructure of the station Klosters and Küblis in an avalanche prone slope at the Dorfberg above Davos. The GNSS algorithm will need some adaptations for evaluating the slope data and those need to be validated. The GNSS data will be used in a new study on glide-snow avalanches. The new location is also suited for a more advanced study on the use of only one GNSS receiver and a Virtual Reference Station for determining SWE; a Reference Station is located in Davos, however, at a different elevation. Therefore, we will explore how atmospheric effects influence the estimation of SWE by using a virtual reference station. The GNSS systems in Laret and Weissfluhjoch will be operated as in the previous winters.

The data collected during the last two winters also allow improving the densification model used in the GNSS algorithm; this should further improve the accuracy of SWE estimation.

Moreover, ANAVS developed a new algorithm based on multi-frequency GNSS signals that should allow a faster and more accurate estimation of SWE. Such a new system was installed in Laret in October 2020 and will be tested during the next winter. Using the multi-frequency GNSS signal, it should be possible to achieve a larger frequency in the GNSS-derived SWE (ideally up to 1 hour).

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