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Using GPS for snow depth and volume measurement of centennial avalanche field in High Tatras

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ABSTRACT

Heavy snowfall in the High Tatras at the end of March 2009 was the cause of several avalanche falls in the Žiarská valley of the Slovakian High Tatras Mountains. The resulting avalanche field was almost 28 ha. The event was classified as a centennial avalanche, one of the biggest in modern history in Central Europe. Snow pack was measured by accurate differential GPS technology. Snow depth and avalanche field volume were calculated using a comparison between avalanche and terrain surfaces. Considering the inaccuracies of the photogrammetric digital elevation model, most likely caused by vegetation, new terrain surveying was required after the snow pack melted in October 2009. The results confirmed that deep snow packs even in rugged terrain can be accurately surveyed by GPS technology.

1. Introduction

The Western Tatras are a continuation of the High Tatras and lie near the outer span of the Western Carpathians. They extend across an area of 29,177 ha ranging in altitude from 700 to 2248 m (the highest peak is Bystrá). The entire mountain massif has an elongated shape along an east–west axis. The main ridge also runs in this direction, and part of it forms a section of the border between Poland and Slovakia. Several ridges project out from the main ridge in a north–south direction, and the northern lateral ridges are lower than those to the south. The six lateral ridges projecting to the south divide the Jalovec, Žiarská, Račková, Jamnická, Kamenistá and Tichá valleys. The ridges projecting to the north divide the valley of the Studený stream. The incidence of glaciers gives rise to glacial valleys with pronounced sills at the ends of the valleys. The topographical characteristics result in frequent occurrence of avalanches. Based on the magnitude, size and abundance of these avalanches, the Western Tatras can be ranked among ranges with the most frequent incidence of avalanches in the entire Western Carpathians (Kňazovický, 1985).

From a climatological perspective, the Western Tatras lie in a cold zone of alpine type characterized by an average temperature of around 10 °C in July. Elevation above sea level considerably influences temperature conditions (e.g. Liptovský Hrádek, 645 m—annual average temperature of 6.2 °C; Kasprový vrch, 1987 m—0.8 °C). Precipitation levels in the Western Tatras are determined primarily by the influence of the Atlantic Arctic Frontal Zone advancing into Central Europe along with northern and western circulation. The orientation of the main ridge along an east–west axis in the direction of the prevailing circulation divides the entire region distinctly into windward and leeward. The orographic proportions of the range variously distort the direction and speed of circulation. The characteristics of the general circulation are mostly conserved in the peak and crest areas, while in the lower ridge areas westerly winds predominate. In the valleys, the prevailing wind direction is determined by their orientation with a predominant direction down along the valley (from internal source of Mountain Rescue Service Slovakia, 2009).

The Western Tatras' topographic features, alpine character, low forest density and large altitudinal differences also influence the distribution and make-up of precipitation during the year. The proportion of snowfall, its abundance and the duration of snow cover also determine the drainage ratios of the terrain. A pronounced drainage maximum in May caused by the considerable snow melt at the end of April and start of May divides the hydrological year (from internal source of Mountain Rescue Service Slovakia, 2009). The topographical nature of the Western Tatras creates an ideal environment for the occurrence of avalanches. Avalanche paths are generally characteristic by large start zones, and wide and long slide paths and run-out areas are directed at the opposite slope or veer toward the lowlands.

Žiarska valley is located in the center of Western Tatras and belongs to the most visited valleys in whole Western Tatras (Fig. 1). In the middle of the valley is situated the Žiarska cottage providing services for visitors such as lunch and accommodation. During winter season it becomes the center of freeskiing and skialpinism. A roadway leading to cottages (Žiarská cottage and a Mountain Rescue Service

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Fig. 1. Location of Žiarska valley in Slovakia.

station) and to a ski lift runs through the Žiarská valley. The roadway passes along the Smrečianka stream for nearly its entire length and according to the register of avalanche paths is immediately threatened by 16 avalanche paths from the east and 13 from the west. Of these, 16 paths have a start zone above the upper border of arboreal vegetation and 13 in the forest zone (Fig. 2). The most problematic are the large avalanche paths from the steep slopes of Baranec (avalanche slopes nos. 14 and 16), from Príslop (avalanche slopes nos. 54 and 55), the Jalovec mountain pass (avalanche slope no. 56) and Ráztoka (avalanche slopes nos. 57, 58 and 59) (from internal source of Mountain Rescue Service Slovakia, 2009).

The Slovak Mountain Rescue Service's Centre for Avalanche Prevention in recent history has documented a large number of avalanches, some of which have even endangered human lives as well as other objects in the Žiarská valley.

The first documented breach of the access road dates back to 18 April 1983 (avalanche slope no. 54). The road has been encroached much more often at other times due to the destroyed forest stand. Of the avalanches with the greatest magnitude, the avalanche of 5 April 1985, which also occurred on avalanche slope no. 54, should be mentioned. With a fracture 450 m wide and up to 0.8 m deep at an altitude of 2000 m.a.s.l., the avalanche occurred over a distance greater than 1600 m and between 40 and 180 m wide. The resulting debris deposit in the valley was 1010 m long, between 40 and 180 m wide, and 0.6–18 m high. A great avalanche with a fracture length over 2200 m fell on 19 January 2000 around 13 hours. This avalanche, with a length of 2300 m and a width exceeding 200 m, occurred due to a combined fracture of avalanche slopes nos. 56, 55, 54, 53, 52 and 51 with a concentration of the slide path in the central channel of Príslop (no. 54). The slab avalanche was caused by new snow and led to significant damages on forest stands to an extent of 10–12 ha. The deposit was 100–200 m wide and nearly 1000 m long, with a maximum height of 12 m. The two cottages in the valley were slightly damaged, and 3 people were endangered, of which one was buried and two were partially buried.

The largest avalanche event, however, occurred in the spring of 2009. As a result of extreme total precipitation (from 6 to 25 March 2009, overcast and frosty weather with constant snowfall predominated in the High Tatras region with the exception of a single day), some 100–150 cm of fresh snow fell over the course of 2 weeks (see Graph 1). The substantial snowfall combined with the low temperatures created ideal conditions for avalanches. The snowfall, moreover, was accompanied by strong winds, which resulted in unstable snow packs on leeward slopes. Avalanche activity was recorded in almost all valleys of the High Tatras. While slab avalanches predominately occurred, loose snow avalanches also occurred occasionally on grassy slopes.

In the morning hours of 25 March 2009, 7 large slab avalanches successively broke away in the Žiarská valley and the snow mass formed a nearly 2-km long deposit. A powder snow avalanche with an average fracture height around 1 m completely flooded the bottom of valley. Both cottages were again damaged, as well as bridges on the access road and tourist signs. An automated meteorological station located next to the cottage also was destroyed. According to survey statistics, it was one of the largest recorded avalanche in Central Europe in modern history. The general sight of avalanche impacts in Žiarská valley is shown in Fig. 3.

As part of the cooperation between the Slovak Mountain Rescue Service's Centre for Avalanche Prevention and the Department of Geoinformation Technologies of the Faculty of Forestry and Wood Technology of Mendel University in Brno, a comprehensive surveying of the avalanche surface using accurate GPS instruments was conducted on 15–16 April 2009 approximately 3 weeks after the avalanche fell. The goal of the surveying was to ascertain the maximum snow depth in the avalanche location and also to calculate its total volume.

2. Methods

The measurement of snow depth is conducted every day in the Czech Republic and Slovakia (former Czechoslovakia) through a network of climatological stations and has a many year history starting at the end of the 19th century. Snow surveying at meteorological and climatological stations is conducted through regular readings on snow-surveying rods, while at modern automated stations it is done through automatic measurements using a laser. Although data from the stations provide a more detailed time series of measurement, they often represent only the immediate surroundings of the station with the same altitude above sea level and topographical configuration. Long-term surface mapping of snow depth has

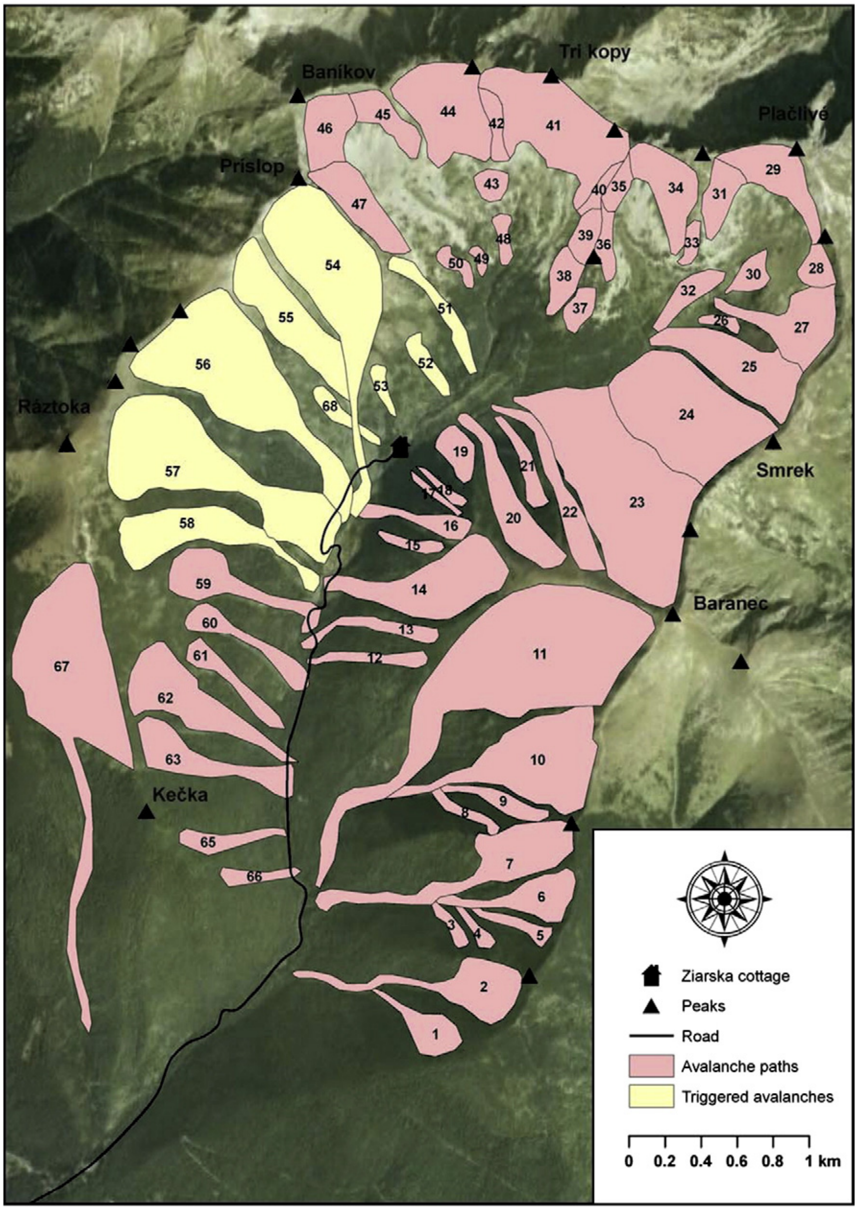

Fig. 2. Avalanche paths in Žiarská valley.

been carried out in the High Tatras region, for example, in the Jalovec valley, since 1987 (Holko, 2008). Even these measurements, however, have only a spot character with low spatial density and thus reflect rather the variability given by elevation gradient and position within the valley.

To calculate the volume of snow in a larger area where it is not possible to use classical measurement methods with the help of snow-surveying rods, methods based on the relative difference in above-sea-level elevation of the snow surface and terrain surface must be used. A basic condition for the application of this method is, therefore, the availability of spatial data about the topography of the terrain under the snow (in the form of contour lines or a digital terrain model). Contour lines obtained using stereophotogrammetry remain the most accessible and hitherto most used source for generating a digital terrain model. One disadvantage of stereophotogrammetric evaluation of hypsometry is its low height accuracy (2–5 m), which may produce an inaccurate hypsometry evaluation depending on the nature of the vegetation (Brázdil, 2009). The most accurate and, at the same time, fastest method of surveying an area's hypsometry is the ground and aerial laser scanning currently being extensively developed. Laser scanning is commonly used in civil engineering applications (Pfeifer et al., 2001), for topographic mapping (Kraus and Pfeifer, 1998, 2001), for monitoring landslides (Rowlands et al., 2003; Glenn et al., 2006) and a range of other applications including generating digital models of surfaces including snow and ice surfaces Prokop, 2008). Accurate hypsometry data for modelling a terrain or snow and ice surface also can be obtained with the help of data from remote land surveying using radar altimetry and radar interferometry (Schanda et al., 1983; Gubler and Hiller, 1984; Rosenthal and Dozier, 1996; Holmgren et al., 1998; Markus et al., 2006; Yankielun et al., 2004; Foppa et al., 2007; Schaffhauser et al., 2008).

The methods of remote land surveying and laser scanning enable very fast collection of information about the monitored phenomenon. In the Czech Republic and Slovakia, however, these remain very expensive. Alternatively, accurate global navigation satellite systems (GNSS) can be used for measurement that is both accurate and fast.

The development of GNSS and the gradual increase in the accuracy of instruments raises the possibility of using these tools even for accurate topographical and hypsometrical surveying including to generate digital terrain models. A condition for achieving high accuracy (on the order of cm or mm) is, on the one hand, the use of differential corrections either in real time or post-processing and, on the other hand, good access to the phase component of the GNSS signal, i.e. very low signal disruption by trees, forest stands, topography or other objects (August et al., 1994). The positioning of GNSS instruments is therefore often limited to areas without vegetation and with good satellite visibility (Deckert and Bolstad, 1996). Practical uses for generating accurate terrain models can be found, for example, in mapping agricultural soil (Coyne et al., 2003; Shannon et al., 2002), field work for constructing roads, rock formations (Maerten et al., 2001) or even for mapping snow depth outside of forest stands (Hurd, 2007). The use of this technology in practical surveying is quite common, and thus we focus solely on concrete problems of mapping snow depth.

Abroad, problems in measuring snow depth and volume have been dealt with, for example, by Hurd (2007), who tested the method of differential GPS measuring on a snowdrift over 2 km long in Alaska and compared the results with a detailed measurement of transverse profiles using snow probes. The source information about the terrain's topography was a digital model of the surface created on the basis of interferometric data from IFSAR radar. To create a snow depth model, a total of 5 various interpolation techniques were used with the best results achieved using interpolation of the nearest neighbour (root mean square error 21.29 cm). In the Czech Republic on the territory of the Krkonoše National Park, differential GPS measuring was used to ascertain the depth of snow on the “Map of the Republic” snow field (Hejcman et al, 2006).

2.1. Surveying avalanche surface using GPS

The surface of the avalanche field was surveyed from 15 to 16 April 2009 using accurate GPS devices with the help of a fast kinematic method. This specifically involved the configuration of 2 Topcon Hiper Pro surveying GPS devices as well as 2 Trimble GPS devices (1 GeoXT and 1 ProXH). Measured data were convert to Czech and Slovak national coordinate system S-JTSK Krovak (defined by Bessel ellipsoid and Krovak conic projection) with use of mean sea level above Baltic Sea for elevations.

When used for RTK (Real Time Kinematic) measurement along with a radio modem, the configuration of the Topcon Hiper Pro surveying GPS devices achieves a degree of accuracy on the order of centimeters in both horizontal and vertical directions and thus enables detailed surveying of the planimetrics and hypsometry (see www.topcon.co.jp, 2010). Considering the extent of the surveyed avalanche (28 ha) and the time demand of measuring, it was also necessary to involve less accurate devices from the company Trimble

Graph 1. Course of snow depth, temperature and wind gust and wind speed during March 2009 (automatic meteorological station near Žiarská cottage).

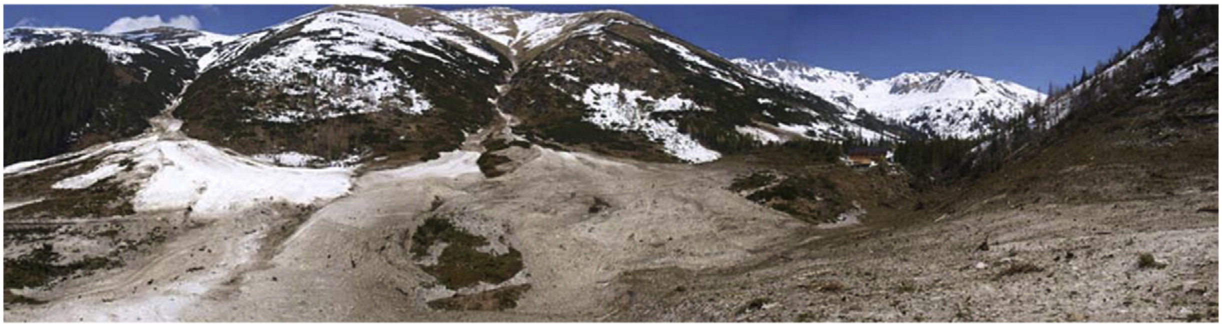

Fig. 3. General sight on the avalanche field in Žiarská valley.

with an indicated positional and height accuracy of around 50 cm when used for differential corrections (see www.trimble.com, 2010).

Accurate localization of the position and height of a point using GPS is possible only when using so-called differential corrections obtained from the nearby reference station (GPS device with phase measurement placed at the point of known coordinates) either in real time (RTK method) or after completing the measurement in the form of so-called post-processing. Considering the isolation of the locality (only minimal signal of GSM networks, large distance from trigonometric points), it was first necessary to accurately locate and stabilize the base network of reference points for measuring differential corrections. This network was surveyed using the static measurement method of the Topcon Hiper Pro device (observation period of ca. 30 minutes at the point) with subsequent post-processing correction using data from the SKPOS (Slovakian GNSS reference station network).

The resulting point grid arose by a combination of data measured using the RTK method with a Topcon Hiper Pro device and data from Trimble GeoXT and ProXH devices made more precise through post-processing. During surveying, emphasis was placed on an appropriate selection of planimetric and hypsometry points in order to capture important fracture points and the edges of the avalanche field. Despite the relatively large eclipse of the horizon by surrounding peaks, the predominant part of the area has very good conditions for satellite signal reception. Problems arose only in the upper sections of steeper slopes and in places near forest stands and mountain pine as a result of loss of the phase element of the signal in such locations, and even the entire GPS signal in certain places, due to the eclipse of the horizon by surrounding peaks and forest stands. Although all devices used have technology eliminating reception of a reflected signal (Trimble EVEREST technology, Topcon Multipath), a preliminary evaluation of the measured data showed that in locations with impaired signal reception the Hiper Pro device, due to loss of the phase element, shows very large positional and height deviations. Therefore, only Trimble devices, which still manage to process the code signal element with sufficient quality in case of loss of the phase element, were used on exposed slopes.

The accuracy of the selected method of GPS measurement using Trimble devices was tested on a trial polygon with similar conditions for measurement (1 second interval, open space with several trees, good availability of GPS signal) near the Faculty of Forestry and Wood Technology in Brno at more than 200 points in comparison with coordinates measured by the RTK method. Thanks to consequent cooperation with the GEODIS company (one of leaders in surveying, airborne laser-scanning and remote sensing in Central Europe) we gained high precision data from airborne LIDAR for this location and we could compare accuracy of LIDAR even practically. The elevation data comparison of the most precise RTK method with Trimble devices and LIDAR is shown in Table 1.

The measured data of avalanche field were processed using the software Topcon Tools and Trimble GPS Pathfinder Office and exported into shapefile format for further processing. A basic evaluation of the measurement results was carried out using a 3D model of the avalanche surface created in an application of the ArcScene software ESRI ArcGIS 9.3 using the extension 3D Analyst (TIN model—Triangulated Irregular Network). The main advantage of TIN besides speed of interpolation is especially the easy identification of local inaccuracies, while one disadvantage, on the other hand, is the surface linearity in places with an insufficient number of measured points and the resulting generalization. After eliminating erroneous measurements, interpolation thus was carried out using the tool Topo To Raster, which creates the so-called hydrologic correction model of the surface taking into account the actual erosion–denudation processes, with a total of 13,000 points used for the interpolation.

In the first phase of processing the result, the actual snow depth and total volume were calculated by subtracting the surface of the avalanche field from the digital elevation model (DEM) created using Topo To Raster from contour lines with an interval of 10 m (the contour lines were created based on stereophotogrammetric evaluation of aerial pictures). The accuracy of digital elevation model is given by the precision of the hypsometric base used. Used contour model was created by the stereophotogrammetric processing of aerial photographs as part of military topographic mapping during 1952–1957 both for the Czech and Slovak Republic (former Czechoslovakia). The mean altitude error of the data reaches 0.7–1.5 m in bare terrain, 1–2 m in urban areas and 2–5 m in forested areas (Brázdil, 2009). For presentation purposes of the Slovak Mountain Rescue Service, the model was supplemented with the surrounding area created from the contour lines of SMM 50 (State Military Map 1:50,000). Upon combining the interpolated surface of the avalanche field with the model of the terrain from contour lines, appreciable inaccuracies were discovered in both position and height of contour lines. Here and there, the terrain exceeded the avalanche, while in other places it was far below it. Positional deviations of crest lines and thalwegs also were substantial. At least the approximate maximum depth of snow and its volume were calculated by a partial positional and height correction of the digital topography model. The resulting map of snow depth and the value of its total volume were therefore substantially influenced by the inaccuracy of the hypsometric model and thus provided only a general idea of these values.

A comparison of measured data with the available hypsometric basis demonstrated the need for a new detailed survey of the

Table 1
Comparison of Trimble GPS and LIDAR elevation data with RTK method.

Technology	LIDAR	Trimble GPS
Mean	0.312	0.645
Median	0.297	0.592
Maximum	0.96	1.762
Minimum	0.000	0.000
Standard deviation	0.216	0.412

Table 2
The results of avalanche field measurements.

Avalanche field area	282,144 m^2
Avalanche field cubature (*25th March 2009)*	993,222 m^3
Cubature of 1 cm of snow in avalanche field	2821 m^3
Mean snow depth	3.5 m
Maximum snow depth	19.9 m
Number of elevation points for avalanche interpolation	13,000
Number of elevation points for terrain interpolation	17,000

topography after removing snow in the avalanche site. Nevertheless, the following conclusions can be drawn from the results of surveying the avalanche surface:

- The generated model confirms the applicability of the method used for the purposes of measuring.
- For the given purpose compared to estimations of Slovak Mountain Rescue Service, both types of instruments achieve good accuracy for avalanche visualization.
- Despite their lower measuring accuracy, Trimble instruments achieve better results in places with worse signal reception and in that respect prove more suitable for the given purpose.
- Despite good results, the model requires additional office adjustments, primarily elimination of inaccurate points.
- Contoured data cannot be used for accurate calculation due to low accuracy, and detailed survey of terrain is required for higher precision of avalanche model.

2.2. Surveying the terrain

To determine the actual volume and depth of snow, a new survey of the topography in locations of the avalanche field was conducted after shrinkage of the avalanche during the period 5–7 October 2009. Despite choosing the latest possible time of measuring, snow had not fully thawed in those places with the greatest accumulation of snow and remnants of the avalanche thus were still evident through autumn. Scattered heaps over 4 m high still remained. Very soon after the avalanche fell, the Smrečianka stream, which flows through the valley, hollowed out a tunnel over half a kilometer long in the mass of

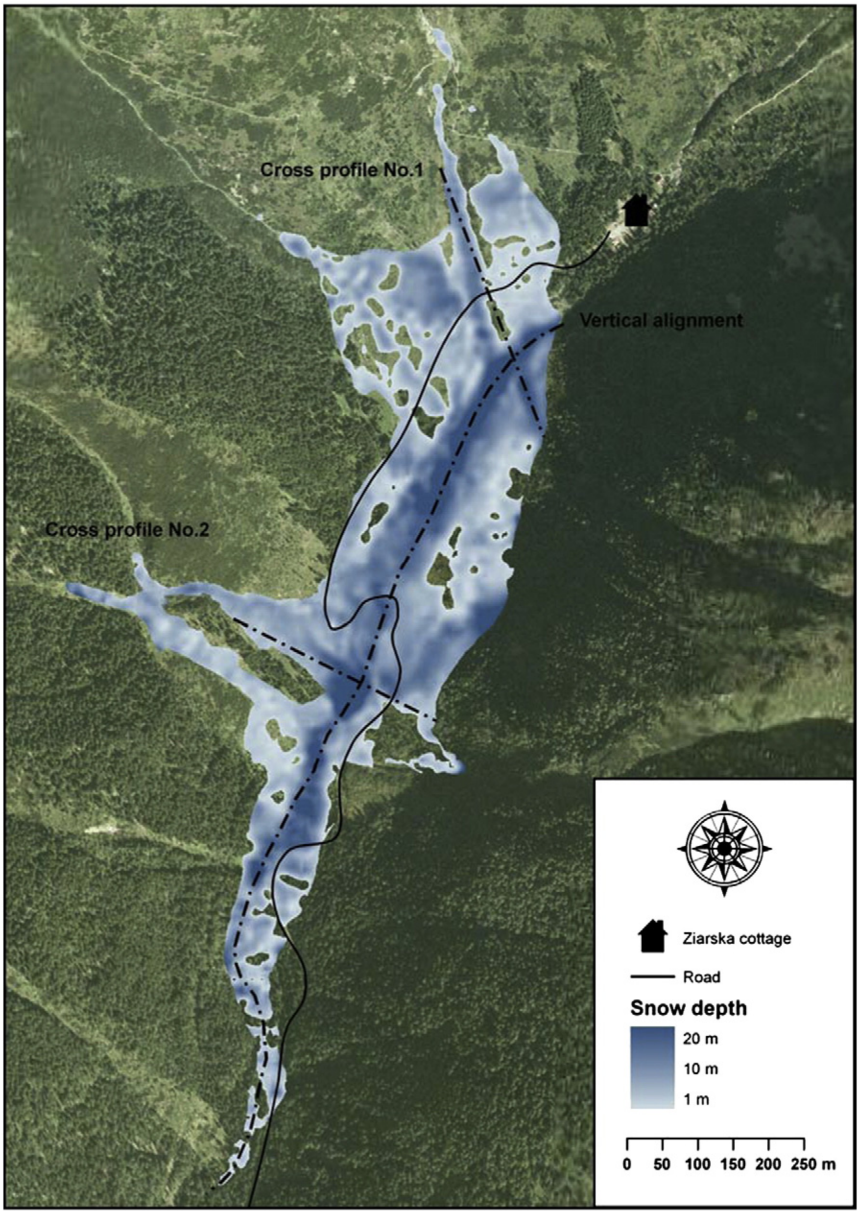

Fig. 4. Depth of snow in avalanche field (25th March 2009).

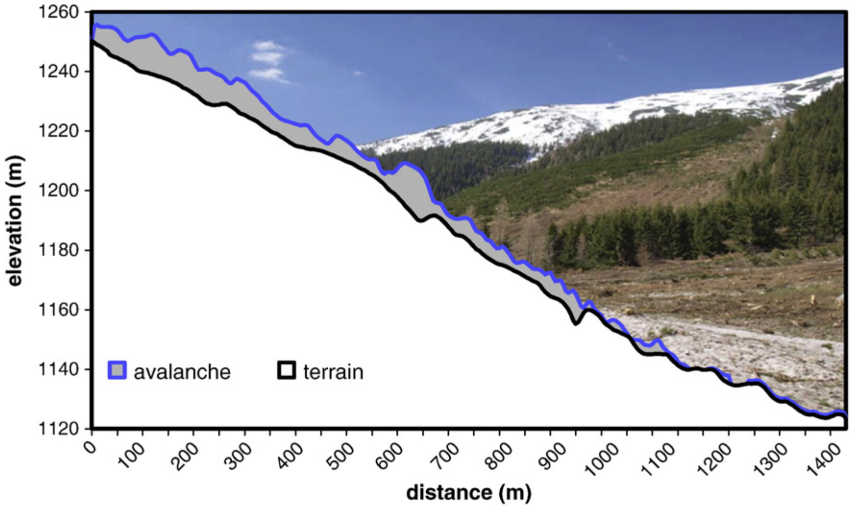

Fig. 5. Vertical alignment of avalanche field.

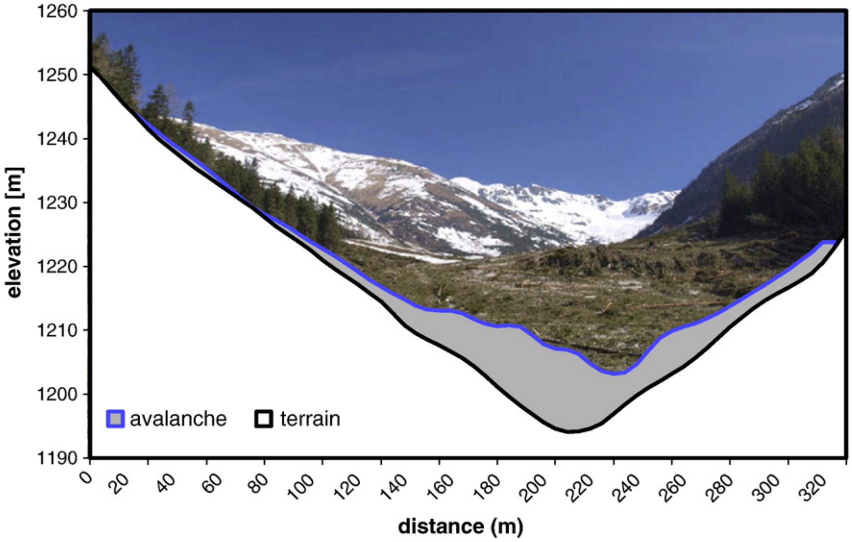

Fig. 6. Cross profile of avalanche field no. 1.

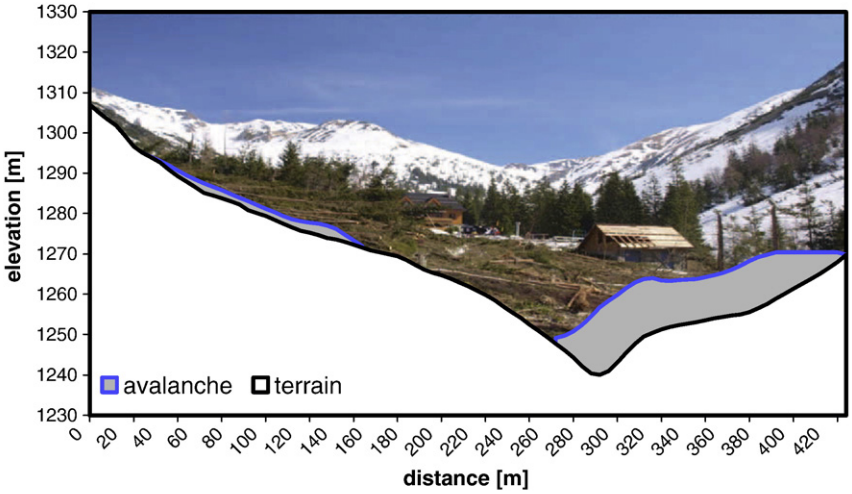

Fig. 7. Cross profile of avalanche field no. 2.

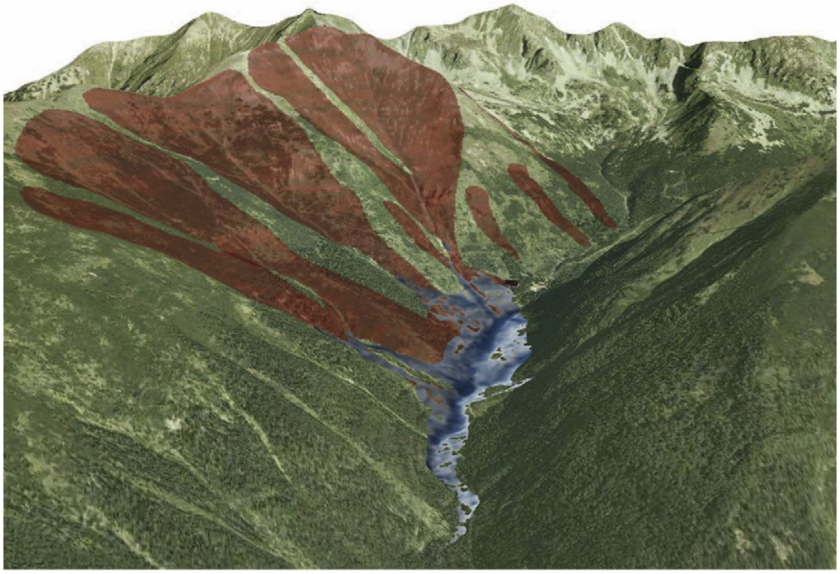

Fig. 8. Avalanche field and triggered avalanches in three dimensional model of Žiarská valley.

snow. The remains of the tunnel at a length of some 40 m could still be observed as of the end of October 2009, and it is possible that they have remained there to date. Just days after the new measurement of the terrain, nearly 1 m of new snow fell in the Žiarská valley and it is therefore more than likely that we will encounter the remnants of the centennial avalanche also in the next year.

The resulting digital topographic model was generated by interpolation of ca 17,000 points using the same procedure as for the avalanche model. Following the reciprocal subtraction of the models in the software ESRI ArcGIS 9.3, the total determined volume of snow was 993,222 m^3 over an area of 28 ha with a maximum thickness of 19.9 m. If this volume of snow were to be distributed evenly over the area of one football field, it would reach a height of 153 m. Considering the extremely high temperatures in the month of April, the snow melted quickly (ca 10–20 cm/day). For this reason, it can be expected that the snow depth at the time of measuring was 1–2 m lower. To give an idea, upon 1 cm of snow thawing the total volume of the avalanche fell by approximately 2800 m^3.

The measurement results were compiled into a table (Table 2), map images, and lengthwise and transverse profiles (Figs. 4, 5, 6, 7, 8).

3. Results and conclusion

The measurement results demonstrate the applicability and efficiency of GPS instruments for detailed surveying of topography or snow cover even in locations with impaired signal reception such as deep mountain valleys. Experiences from the measuring indicate that although the RTK measurement method achieves very high-quality results when measuring on a clear area the use of this method is limited in more challenging conditions with greater shielding of the signal by the topography or woody vegetation. Compared to other techniques, LIDAR data give more accuracy, but cost of this method does not make it suitable for such small area. According to our measurement on the trial polygon, LIDAR achieves double precision compared to Trimble GPS (MEAN 0.312 m vs. 0.645 m—Table 1.), but in scale of large avalanche field is even half meter precision adequate. Statistic parameters as maximum and standard deviation show the stability of GPS accuracy with only small fluctuations. Early and fast acquisition of airborne LIDAR data or interferometric satellite data does not make any problem even in the Central Europe, however it claims higher demands on data processing (especially time, software). Due to lack of time (high temperatures throughout April caused rapid snow melting—around 10 to 20 cm per day) and due to mentioned higher costs was finally chosen GPS measurement. The quality and availability of DEM hypsometric data sets thus prove to be fundamental for GPS volume measurements under mountain region conditions. These data sets show considerable height errors, and thus GPS cannot be directly applied for determining avalanche parameters without subsequently measuring the terrain. The results of article prove utilization of GPS devices for snow cover depth. In contrast with other techniques (LIDAR, IFSAR), these measurements are applicable to practical everyday activities of mountain rescue service for local measurements and avalanche danger identification. At the same time, the results will serve as permanent documentation of the aftereffects of this historical avalanche for other purposes of the Slovak Mountain Rescue Service's Centre for Avalanche Prevention as well as rescue units of other countries.

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