POSSIBILITIES AND PROBLEMS FOR THE INTEGRATION OF POINT CLOUDS FROM DIFFERENT SURVEY METHODS

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ABSTRACT

With the increasing use of 3D point data in various fields of environmental research (e. g. monitoring of landslides or debris slides), questions about the acquisition of the data material, the quality of the data and, thus their integrability into an already existing geodatabase become more and more important. In the present work, an attempt was made to combine point clouds from a wide variety of survey methods into an overall data set of the highest possible quality. On the one hand, terrestrial laser scans generated by Riegl VZ-600 2018 and, on the other hand, image data acquired by UAV flights (DJI Phantom IV,) during the same field campaign served as a basis for this. Reconciliation and combination of these (partly unregistered) raw data sets was performed using Riscan Pro and Agisoft and CloudCompare software, respectively, assessing the quality of the product by comparing it with official ALS of Slovakia or by defining a maximum allowable Root Mean Square Error (RMSE). It was shown that a subsequent integration of 3D data from different sources can certainly lead to satisfactory results, although the problems of the methodology (unfavorable behavior of larger water surfaces, surface changes between the recording times of TLS and ALS, shaded areas in the TLS, ...) became obvious.

Keywords: terrestrial laser scanning, unmanned aerial vehicle, structure from motion, point cloud processing, High Tatra Mountains

INTRODUCTION

One of the most widespread and, in view of the advantages arising from it, rightly often used areas of point clouds acquired terrestrially or airborne is the application of this data material in disaster control research. Regardless of whether it is the simulation of flood scenarios, the inventory and documentation of mass movements or the monitoring over a certain period of time [1,2], the possibility of acquiring large amounts of geodata comparatively quickly and almost area-wide. Apart from the necessary and comparatively large expenditures in the form of hardware and software costs, but also in the form of the necessary expertise of the acquisition team, the difficulties and problems that can occur, especially in extreme investigation areas such as high mountain areas, are often underestimated when planning the field work. Such a scenario, in which external influences and problematic conditions have seriously jeopardized the results of a carefully planned measurement campaign, serves as the background for the project presented here. The Velická dolina study area is located in the eastern part of the High Tatras about 10 km northwest of Poprad in the immediate vicinity of the lake of the same name (Velické Pleso) situated at an altitude of 1665 m above sea level. The main axis of the valley is about six kilometres long and extends from the road Cesta Slobody to the mountain

Velický štít on the main ridge of the High Tatras between Zadný Gerlach and Východná Vysoká. The valley covers an area of about 5.7 km². The refuge, today mountain hotel Sliezsky Dom, was built in 1895 and is situated at the southern end of Velické Pleso. Morphologically, it is a part of a map staircase, which is important from the point of view of elevation, because the area is framed by steep rock walls both laterally and inwards from the valley, and therefore large areas of the terrain are neither accessible nor visible. As a result of this over-division of the relief and its exposed position, the area is also characterized by large-scale mass movements that manifest themselves in the landscape in the form of mighty debris and rubble fans (Fig. 1).

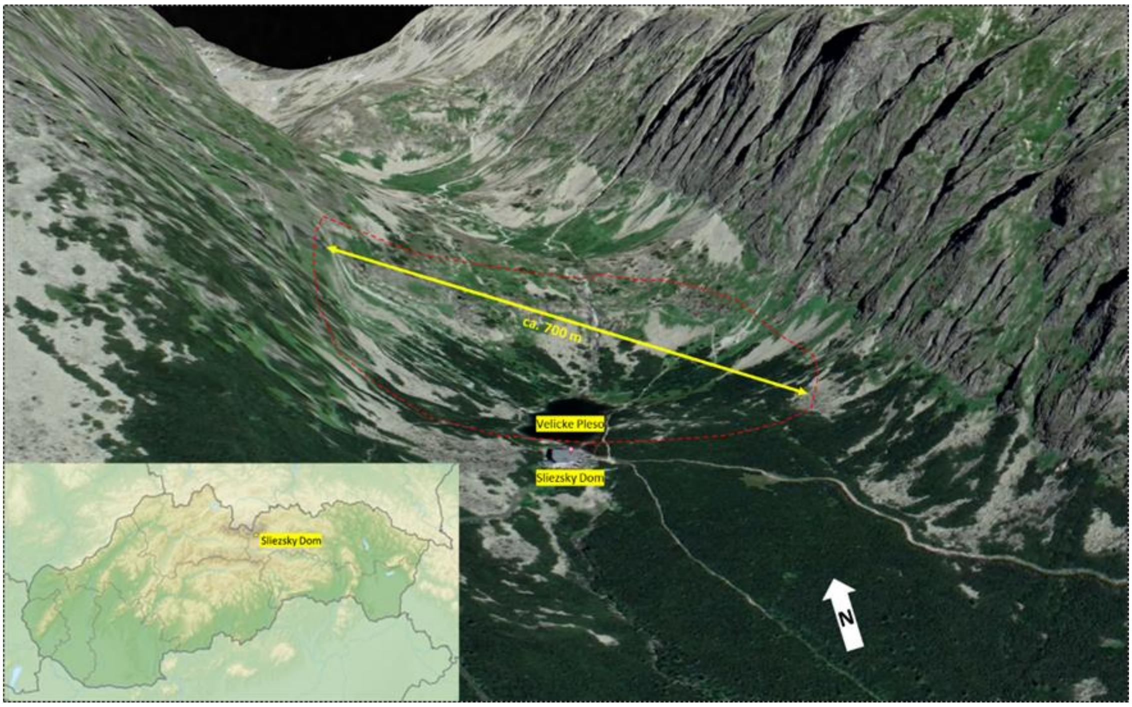

Figure 1. Location and relief of the Velické Pleso/Sliezsky Dom investigation site.
The red dashed line delineates the area covered by TLS and UAV measurements.
Source: Google Earth, modified by the author.

This characteristic - poor accessibility combined with shadowed areas - suggested the use of a combined land/airborne acquisition strategy. In this way, the advantages of both survey methods are combined and as a result, high-resolution scans could be obtained in addition to the texture information of the photogrammetric drone images. Of course, this requires careful planning of the work package and their interdependencies as well as the appropriate execution.

Figure 2. View over the western flank of Velické Pleso towards Kvetnicová veza (2433 m).
Source: Sulzer, 2017.

The photograph (Fig. 2) documents the characteristics of the study area. At the lower part of the rocky, steep terrain (ca. 1800 m), partly active debris cones or debris channels emerge from the incised flanks, which then gradually change into shallow mostly inactive debris fans. Towards the shore of the lake (ca. 1660 m) the episodically water-bearing gullies change into small alluvial fans. The typical vegetation here is patches of leghorn (Pinus mugo), which is difficult to walk on and is interspersed with herbaceous vegetation, especially in the lower areas. At the upper edge towards the rocky areas there are late alpine grass heaths.

The starting point of the present study was the attempt, envisaged at the beginning of 2018, to investigate more precisely the development of mass movements in the vicinity of the lake; it should be emphasized in this context that, at the time of the project planning, no DTM was available from the official side that would have met the requirements of the study. The data material used in this work with the resolution of 1 m originates from aerial surveys that took place between 7.8. and 8.8. 2018. Not least in consideration of the coarse-blocky nature of the terrain surface, the goal of the campaign was to create an elevation and surface model that would be significantly better in terms of resolution than the data available up to that point.

The equipment used essentially comprised 3 components, with the location of the required ground control points, reflector and scanner sites being carried out using dGPS in the form of a kinematic RTK solution. The terrestrial scans were performed using a Riegl Z620; this system is a class 1 rotating laser with a maximum range of 2000 m which - with a field of view of 80° by 360° - is capable of acquiring about 11000 points per second. The beamwidth spread is 0.15 mrad (equivalent to 15 mm expansion per 100 m), the minimum possible angular step width is 0.004°. The latter corresponds - in case of an average object distance of 700 m - to a theoretical point spacing on the object of about 5 cm [3]. For the image data acquisition from the air, a flying drone was used. The naturalized term Unmanned Aerial Vehicle (UAV) is used for this purpose in this paper. This is also known by names such as Unmanned Aerial System (UAS), Remotely Piloted Vehicle (RPV) [4]. The above terms are often used as synonyms. UAVs provide a platform equipped with a photogrammetric measurement system, including a small or medium still video or video camera, thermal imaging or infrared camera systems, airborne LiDAR systems, or a combination thereof [5]. A DJI Phantom 4 was used in Velické Dolina because of its robust and compact design and its ability to remain stable in flight despite its light weight of 1380 g, even in the strong winds often prevailing in the study area. This advantage is achieved by a new design for the time with improved aerodynamics (the Quest 200 fixed-wing aircraft, which was also intended for use, was not used on the one hand because of the constriction of the cirque area and the gusty winds). The DJI Phantom 4 is a Quadro copter with a 4K camera and allows a flight time of about 28 minutes by using a battery with a capacity of 5,350 mAh. The image format can be selected between RAW and JPG images, whereby the JPG formats are sufficient for further processing in Agisoft Metashape.

With regard to the objective of the research project (recording of the slope areas around Velické Pleso classified as morphodynamically active as a basis for future monitoring projects), the work plan included a complete and detailed recording of the study area by means of laser scanners; in addition, selected areas were to be covered by means of UAV flight in order to avoid data gaps due to shadowing and to increase the data density. The RTK-based measurement of scanner and reflector locations as well as the location of about 50 ground control points served as the basis for the georeferencing of the data obtained in this way. As already indicated, however, unforeseeable technical difficulties with the equipment made it necessary to deviate from this plan. In detail, an unspecified error in the scanner's cabling caused problems with the power supply (and thus subsequently with the device control), so that instead of recording larger, contiguous areas, the focus had to be placed on recording smaller sections of the terrain. This approach made it possible to control the loss of data due to unforeseen interruptions of the scanning process to a certain extent, but it also meant a considerable additional effort and delays in the schedule. Finally, the area was scanned from 5 scan positions with a step width of 0.017°, so that at a distance of 300 m, adequate for the purpose of the investigation, with a point spacing of somewhat more than 10 cm (at 400 m approx. 13 cm), it was possible to calculate with about 126 points on one square meter. Compared to the official Slovak DOM (which at that time was only in the flight stage), this meant that the level of detail was significantly higher. With the quadrocopter DJI Phantom 4, a total of 197 images were taken in 4 flight campaigns.

Table 1. Flight parameters for the UAV campaign Velicko dolina

flight	images/ waypoints	cover area	flight length	altitude above starting point	resolution	front overlap ratio	side overlap ratio
01	39/43	3.67 ha	708 m	100.4 m	4.3 cm	90 %	60 %
02	66/69	2,52 ha	712 m	70.3 m	3 cm	90 %	67 %
03	61/62	2,46 ha	656 m	68.3 m	3 cm	90 %	65 %
04	27/27	2.89 ha	536 m	111,7 m	4.8 cm	90 %	60 %

Since the weather was very unstable with gusty winds, the flights had to be kept as efficient and short as possible. The division of the recording into four individual flights is due to the battery capacity and the necessary safety reserves. Due to the unfavorable wind conditions, not all waypoints of the flight planning could be approached by the UAV controlled by an internal GPS either. However, the missing images could be compensated by the high front and side overlap ratio (90 % and approx. 60 %, respectively). The changing altitudes of the flights result from different starting positions in the study area. The varying flight heights result from the different relief. In steep, rocky regions, a higher flight altitude above ground was selected for safety reasons (risk of collision and winds). Despite these adversities, a geometric resolution between 3 and 5 cm and thus a target resolution of the project with 5 cm could be achieved.

As a result of the previously described collection process, three types of data were created - corresponding to the different acquisition procedures: Unfortunately, the analysis of the scan-relevant control points acquired by means of dGPS showed an unsystematic error for reasons no longer comprehensible at the time of the analysis, which manifested itself in a lateral offset of the position of scan or reflector positions in the order of magnitude between 1.5 m and 3.5 m.

From a huge number of TLS scans, including overview scans with a step size of only 0.2° and about 750,000 data points each, 5 distinct point clouds with a step size of 0.017° and between 22 million and 45 million points (file size: 400 - 700 Mbyte) were selected for further processing. Due to the favorable distribution of the scanner locations around the lake, a sufficient overlap and a significant reduction of the shadowing areas could be achieved. Unfortunately, however, the problems described above hampered not only precise real-world location of these inherently high-quality data but also (due to the lack of accurate measurements of the reflectors) efficient scan-to-scan linking of the individual point clouds.

METHODS

As a consequence of the described problems with the dGPS data, the use of these measurements was completely abandoned in the further processing of the data; instead, recourse was made to the official aerial photo material, the high quality of which (RMSExy = 0.20 m) was sufficient to be able to carry out the necessary rough localizations with an accuracy of +/-30 cm with the aid of the photo documentation created during the measurement campaign and in this way to convert the point clouds from the SOCS (scanner own coordinate system) into a projected system and thus to create the basis for further processing. Only after this step could the generation of a high-resolution surface model be tackled; the concept for this is based on the attempt of an error correction of the raw data by comparison with the official data. This way seems to be possible insofar as both the DTM 5.0 and the DSM 1.0 or the underlying ALS point cloud have sufficiently strict quality criteria. The point cloud data intended for comparison have an absolute vertical accuracy of less than or equal to 0.15 m (related to ETRS89 ellipsoidal heights) or an absolute positional accuracy of 0.30 m (related to ETRS-TM34); for DTM 5.0, these values are less than 0.20 m and 0.25 m, respectively [6]. Thus, a fit of the TLS/UAV data into the supra-regional DSM seems to be within the realm of possibility.

In the next step (data pre-processing), a rough registration of the official ALS data to the TLS point clouds was performed. This was done in the form of a point-to-point transformation over clearly identifiable points in the terrain (ridges, rocky peaks or hiking trails or the lake shore). At the end of this process, there is still a relatively large RMS error of about 13 m, but this value is not too important insofar as this step only served as a preparatory measure to reduce the processing time for the fitting process that was later carried out in an iterative manner. In addition, it should be noted here that certain deficiencies in the TLS data sets were already apparent at this stage, which had the potential to negatively influence the fitting quality. Particularly noticeable was the discrepancy in the water surface of the lake, which had been appropriately corrected in the ALS, while in the TLS point clouds it naturally exhibited reflections, resulting in the need to mask the water surface area for the calculations. Moreover, backscatter effects occurred in the TLS scans, which also had a negative impact on the fitting quality; the latter were minimized by applying a filter whose parameterization (taking into account local maximum possible height differences of the relief, vegetation height, ...) did not pose too many problems. Finally, the question had to be clarified to what extent the inclusion of TLS areas located further outside the study area should be included in the calculations. Since it could not be estimated with sufficient certainty at this point in time whether these data would have a rather positive or rather negative effect on the calculation, it was initially decided not to remove these scans. After the removal of the errors just described, the RMSE could be reduced to 2.28 m, so that it was possible to speak of a sufficiently stable starting point for the next adjustment process. This iterative closest point algorithm (ICP - algorithm) for fine registration of points, lines, polygons and TINs), first presented by Besl and McKay [7], consists essentially of 4 steps, the determination of neighbouring point pairs from the point clouds to be compared, the calculation of the general transformation rule, the execution of the transformation of the point cloud to be registered on the basis of these results and the iterative repetition of this procedure until a defined termination criterion is met. As a prerequisite for the practical applicability of the procedure, as already mentioned, the rough matching of the non-referenced scan to the reference point cloud and its overlap are sufficient, although a merely partial overlap of the two areas generally does not have a serious impact on the result. Thus, even point clouds that - if referenced - have only a relatively small overlap (i.e., a low final overlap value) can be processed. The central element of quality control in this process is the RMSE, whose change is measured after each loop pass. Accordingly, it is not surprising that, in addition to the brute force method (i.e., by a priori definition of a certain number of passes), the magnitude of this change can be used as a termination criterion. In other words, the continuous improvement process is terminated when the RMSE decrease falls below a predefined minimum amount. In the course of time, the basic concept has been revised or refined, especially with respect to the selection of the corresponding points, so that, for example, far outlying points are disregarded (robust ICP) [8], the selection of the correspondences is optimized by using improved data structures (k-tree) [9, 10], or the reduction of the search space via pyramid levels [11, 12]. In the present case, the different acquisition and processing methods of the data or the possibly resulting scale differences were considered insofar as the software was allowed to adjust any scale differences. Furthermore, a random subsampling routine with a threshold value of 50000 points was defined to be able to process the relatively large point clouds quickly; in addition, the speed of the transformation was also optimized regarding the behaviour towards statistical outliers (due to noise or unevenly distributed points).

The local adjustment and the determination of the point distances in the model is done in principle either by defining n comparison points to be considered for the calculation or by using a local reference surface; the aim of this Local Modelling is that it should prevent that the calculation of the point distances is based only on the distance to the n nearest neighbours (Hausdorff distance algorithm), which proves to be disadvantageous especially for comparison point clouds with low density or with "holes" in the dataset [13]. The concept of "local modelling" tries to assume the real surface around the closest point to get a better estimate of the "real" distance. Three concepts are available for this purpose: the use of the plane of least squares of deviation, a 2D1/2 triangulation of the surface sought, or the height function (actually a 6-parameter quadratic function, though both mapping fidelity and computational cost increase in that order. Because of its versatility, the quadratic model was used in the present study, although arguments could have been made for the triangulation method given the surface configuration in the study area.

Due to the sometimes-significant differences in radiometry between the images and variations in geometric resolution, the processing of the data is relatively complex and sometimes necessitates extensive processing steps [14]. According to Colomina and Molina [15], UAV data are also characterized by unstable camera geometries, irregular aerial image block structures (significant deviation from nadir acquisition, highly variable image scale, changing image coverage, and varying flight altitude within a strip), and sometimes large geometric and radiometric variations. This is particularly noticeable in the high mountains with high relief. UAV data have, among others, special unstable camera geometries, low radiometric resolution, etc., which lead to their limited analysis in classical photogrammetric software packages. Structure from Motion (SfM) is a cost-effective and user-friendly photogrammetric technique for obtaining high-resolution datasets at various scales [16]. According to it, the basic principle of SfM method is to derive 3D information from overlapping (stereoscopic) images. The image overlaps of the UAV images are usually very large for the SfM method, ranging from 60-80 %. The software used in this work is Agisoft Metashape Professional. This software allows the processing of RGB or multispectral camera images, into the form of point clouds, georeferenced orthomosaics and digital elevation models. The software has a linear project-based workflow, which is user-friendly even for non-experts. Smith et al [17] give an overview of a typical SfM workflow (Fig. 3).

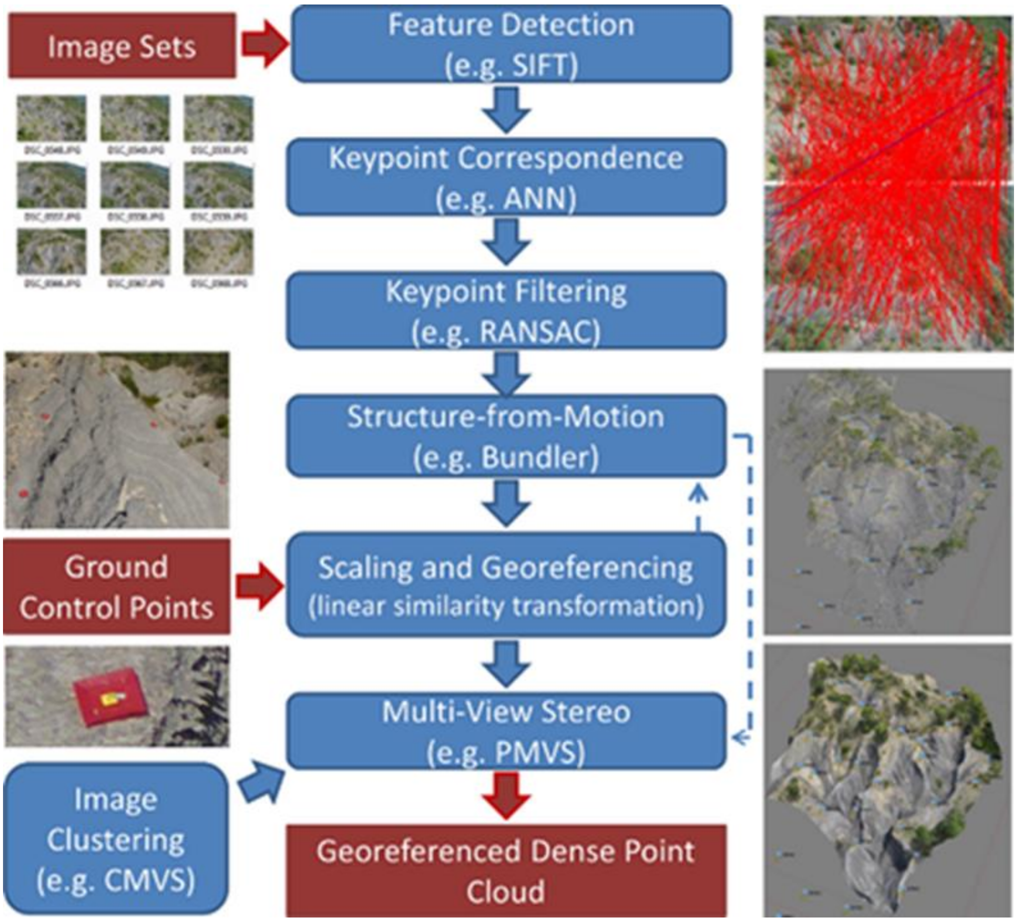

Figure 3. Typical workflow in the production of georeferenced dense point clouds from image sets and ground control points. Inputs and outputs are shown in dark red. In the top right, as a demonstration, matches determined to be valid are shown in red, while matches determined to be invalid are given in blue [17].

This workflow is independent from the used software as well as from the used acquisition platform, because in commercial software packages, like the software used in this work, the exact workflow within the software or single processing steps is not known. The processing of UAV image data in Metashape includes the following main steps: loading photos into Metashape - inspecting loaded images, removing unnecessary images - aligning photos - building dense point cloud - building mesh (3D polygonal model) - generating texture - building tiled model - building digital elevation model - building orthomosaic- exporting results [18]. Some Metashape functions like exporting digital elevation models are only available after the coordinate system has been defined. The software supports setting a coordinate system based on ground control point coordinates (GCP's) and/or camera coordinates. In both cases, the coordinates can either be loaded from the external file or entered manually. Unfortunately, the ground control points (GCP) surveyed with the dGPS could not be used for georeferencing either. Thus, only the camera positions supported by points measured from the official orthophotos could be entered.

RESULTS AND DISCUSSION

As already shown in the presentation of the applied methodology, the quality of the fit - documented by the RMSE to the ALS model - could be increased significantly (to RMSE equal or less than 0.51 m). After a more intensive post-processing of the TLS scans in the form of an improved backscatter filtering but also by masking the originally still included peripheral areas of the scans (comparative calculations had shown their low relevance for the local fitting quality), the RMSE value for the individual point clouds could be reduced to about 10 cm (Fig. 4).

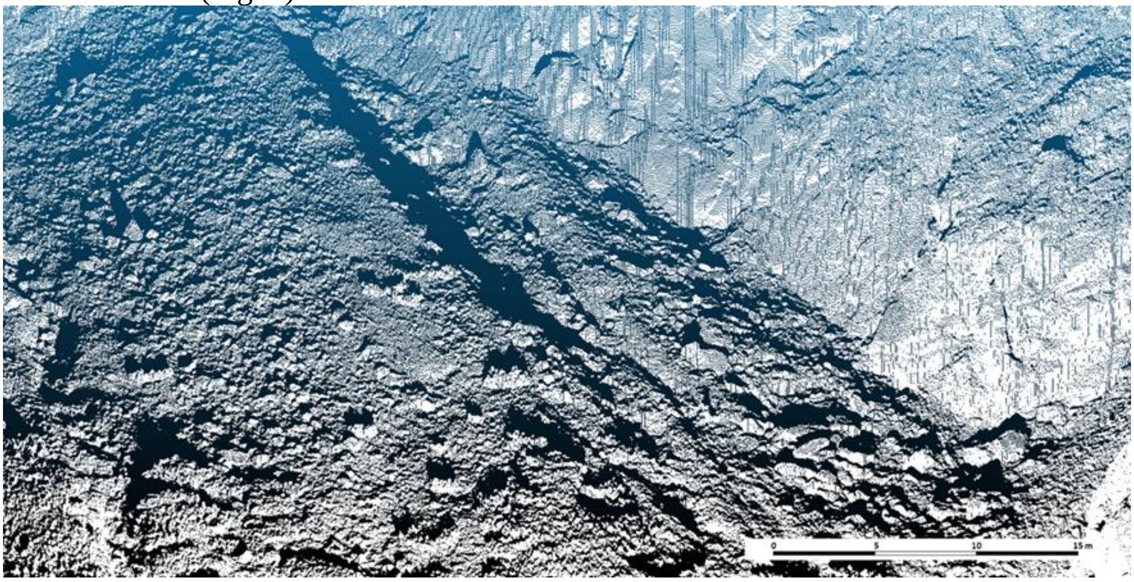

Figure 4. Although the resulting point cloud is too complex to be shown here in more detail, the picture clearly shows two important aspects of the result of the integration process: on the one hand, the high point density/detail fidelity of the surface created in this way, and on the other hand, the partially large, shadowed areas.

Thus, the originally set goal can be considered achieved for the time being, especially since the other potential sources of error are of such a more complex nature that they can only be briefly touched upon in this paper. Although the vegetation in the study area consists almost exclusively of slow-growing cold-resistant scree (Pinus mugo ssp. mugo) or alpine turf, a minimal deviation between ALS and TLS cannot be completely excluded. However, the former were relatively easy to identify and, if necessary, to separate out due to the approximately equal stand growth height. That being said, the steep slopes surrounding the immediate study area could have an impact on the results in that they are the source of large-scale, relatively dynamic debris piles. This coarse blocky material could be responsible for the fact that - even with very small lateral movement - the overturning of a block can provide for recognizable changes in the surface appearance. Finally, differences in the recording systems used (in terms of footprints, recording angles, equipment differences, etc.) can also have an impact on the calculation results. Finally, the attention should also be directed to the further processing of the produced data set. It is understandable that the process presented here directs its focus only to the preparation of the data material, which will most likely be analysed and visualized by users in other working environments such as GIS. In most cases, therefore, conversion to other data models will be necessary. Whether raster (grid) or vector (TIN) models are more advantageous in this case is primarily dependent on the problem or the analysis tools required for it. In any case, the problem of data gaps will again come to the fore in these considerations and will have to be taken into account in the further processing steps. Remote sensing or SfM provides high-resolution orthophotos and surface models (DSM).

Figure 5. Part of the Orthophoto from UAV (2017) with a resolution of 5 cm (left) and (right) Orthophoto from 2019 with a resolution of 25 cm. Source: https://zbgis. skgeodesy.sk/

Fig. 5 presents a comparison between the 2017 orthophoto (5 cm resolution) produced by SfM and the 2019 official orthophoto (25 cm). The level of detail of the terrain information is clear from the plot. This allows the detection of macroscopic terrain structures and in repeat flights, their change. In addition, changes in ground cover, especially vegetation, can be detected and displayed with relatively little effort.

SUMMARY

Based on the research questions that preceded this work, the following results can be summarized at this point: The fundamental question about the basic feasibility of the correction procedure for erroneously acquired data presented here can be answered positively, whereby in the present case the almost simultaneous collection of the official ALS data proved to be very advantageous. The usefulness of the data, which has been greatly improved in quality, is definitely given in view of the significantly higher sampling rate of the TLS scans, but it should not be concealed that this condensation of the point clouds - caused by the special characteristics of earthbound laser scanning as well as by the scanner positions, which are not optimally distributed for the given reason - can only be guaranteed for selected areas of the terrain. The answer to the question of the usefulness of the improved data therefore depends to a large extent on the extent to which shadowed areas or areas not detectable by the TLS are of importance for intended analyses; provided that the same scanner locations are used again for subsequent observations, these data could, for example, be used very well for monitoring landslides. Both the high-resolution orthophoto generated from UAV flights and the surface model can be used for the sensitive high-mountain region as an important data basis for changes in small subareas. Repeat flights allow the generation of spatial changes (e.g. movement of larger blocks by mass movements or by fluviatile processes.). The strengths in the use of UAV data lies in the acquisition of data with high geometric resolution, the high point density and regularity of the derived point cloud, favourable or variable recording perspective for steep mountainous regions. They are flexible and can be used even in continuous cloud cover. The argument of the flexible applicability of UAVs has to be qualified by logistical limitations (availability of personnel and material), meteorological conditions (e.g. strong wind) and legal aspects.

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