EVALUATION OF UAV-BORNE PHOTOGRAMMETRY AND LASER SCANNING FOR 3D TOPOGRAPHIC CHANGE ANALYSIS AT AN ACTIVE ROCK GLACIER

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ABSTRACT:

Point clouds derived from UAV-borne laser scanning and UAV-borne photogrammetry provide new opportunities for 3D topographic monitoring in geographic research. The airborne acquisition strategy overcomes common challenges of ground-based techniques, such as limited spatial coverage or heterogeneous measurement distribution, and allows flexible repeated acquisitions at high temporal and spatial resolution. While UAV-borne 3D sensing techniques are expected to thereby enhance geographic monitoring, their specific potential for methods and algorithms of 3D change analysis is yet to be investigated. In our study, we assess point clouds originating from UAV-borne photogrammetry using dense image matching (DIM) and UAV-borne laser scanning (ULS) as input for 3D topographic change analysis at an active rock glacier in the Austrian Alps. We analyse surface change by using ULS and DIM point clouds of 2019 and 2021 as input for two state-of-the-art methods for pairwise surface change analysis: (1) The Multiscale Model to Model Cloud Comparison (M3C2) algorithm and (2) a recent M3C2-based approach (CD-PB M3C2) using plane correspondences to reduce the uncertainty of quantified change. We evaluate ULS-based and DIM-based change analysis regarding their performance in (1) achieving high spatial coverage of derived changes, (2) accurately quantifying magnitudes and uncertainty of change, and (3) detecting significant change (change magnitudes > associated uncertainty). As reference we use change quantified between two terrestrial laser scanning (TLS) surveys undertaken simultaneously with the ULS and DIM data acquisitions. Our study shows the improved spatial coverage of M3C2 achieved with point clouds acquired with UAVs (+ 60% of core points used for change analysis). For CD-PB M3C2, ULS and DIM point clouds enabled a spatially more uniform distribution of plane pairs used for change quantification and a slightly higher spatial coverage (+6% – +7% of core points used for change analysis) compared to the TLS reference. Magnitudes of M3C2 change were closer to the TLS reference for ULS-ULS (mean difference: 0.04 m; std. dev.: 0.05 m) compared to ULS-DIM (mean difference: 0.12 m; std. dev.: 0.08 m). Similar results were obtained for CD-PB M3C2 using ULS-ULS (mean difference: 0.02 m; std. dev.: 0.01 m) and ULS-DIM (mean difference: 0.06 m; std. dev.: 0.01 m). Moreover, magnitudes of change were above the associated uncertainty in 82% – 89% (M3C2) and 89% – 90% (CD-PB M3C2) of the area of change analysis. Our findings demonstrate the potential of ULS and DIM point clouds as input for accurate 3D topographic change analysis for the study at hand and can support the design and setup of 3D/4D Earth observation systems for rock glaciers and natural scenes with complex topography, such as landslides or debris covered glaciers.

1. INTRODUCTION

Quantification of surface change from multitemporal topographic point clouds is integral for analysing the dynamics of the Earth's surface across many disciplines in geoscientific research (Eitel et al., 2016). Point clouds acquired with UAV-borne photogrammetry using dense image matching (DIM) and UAV-borne laser scanning (ULS) provide new opportunities for 3D topographic monitoring in geoscientific research (Westoby et al., 2012). The UAV-borne acquisition strategy overcomes common challenges of established ground-based techniques, such as occlusion, heterogeneous measurement distribution, limited spatial coverage, and time-intensive data collection. Moreover, it allows flexible and repeated acquisitions at high temporal (up to daily or hourly) and spatial (centimetre point spacing; Zieher et al., 2018) resolution. UAV-borne photogrammetric and laser scanning point clouds have been used for monitoring of, for example gullies (Eltner et al., 2015), landslides (Zieher et al., 2018), and rock glaciers (Hendrickx et al., 2019; Bearzot et al., 2021).

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As different close-range remote sensing techniques provide data with different inherent properties, a naive combination of such data is not possible (Mandlburger et al., 2017). It is rather neccessary to investigate the performance of methods and underlying algorithms for 3D change analysis when applied to data from different acquisition strategies.

Surface change between two epochs of topographic point clouds can be derived in full 3D via direct point cloud comparison. A widely used algorithm for this is the Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague et al., 2013). It considers spatial variability in surface orientation by quantifying change in the direction normal to the local

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surface orientation. Complementing 3D change analysis using M3C2, the correspondence-driven plane-based M3C2 (CD-PB M3C2) algorithm (Zahs et al., 2022) was designed especially for topographic change analysis in natural landscape settings with distinct planar rigid objects, such as faces of individual boulders, and a rough surface morphology in relation to small-magnitude changes. CD-PB M3C2 extracts M3C2 distances as surface change based on homologous planar areas. It was shown to particularly improve the detection of small-scale changes where the target surface change is mainly expressed by movement of rigid objects (Zahs et al., 2022). In addition to the full 3D change information, both M3C2 methods quantify the uncertainty of change. This so-called Level of Detection (LoDetection) separates significant change (magnitude of change $>$ LoDetection) from non-significant or no change (magnitude of change $\leq$ LoDetection), and is of considerable value for confident change analysis and the geographic interpretation of results (Anderson, 2019).

The specific potential of point clouds derived from UAV-borne data acquisition for methods and algorithms of 3D and 4D (3D + time) change analysis is yet to be fully exploited. In our study we evaluate point clouds originating from UAV-borne photogrammetry and laser scanning as input for 3D topographic change analysis at an active rock glacier. We use ULS and DIM point clouds as input for two state-of-the-art methods for pairwise 3D change analysis: (1) The M3C2 algorithm and (2) the CD-PB M3C2 algorithm. Results of change analysis using two ULS epochs and one DIM epoch are evaluated. The evaluation regards the spatial coverage achieved by the different acquisition strategies and the accuracy of quantified change. We further assess the uncertainty estimate associated to changes and the accuracy of distinguishing significant change (change magnitudes $>$ LoDetection) from non-significant or no change (change magnitudes $>$ LoDetection). As reference data we use results obtained from change analysis using two TLS epochs.

Future 3D/4D Earth observation systems will integrate information from different close-range-sensing techniques and platforms for the analysis of surface change. Results of our study can support the theoretical and practical design of future systems for monitoring of complex topographic settings.

2. STUDY SITE AND DATASETS

Our study site is the rock glacier Äußeres Hochebenkar (Figure 1) in the Eastern Austrian Alps (46° 50’ N, 11° 01’ E). Rock glaciers are creep phenomena of mountain permafrost where unconsolidated and ice-supersaturated debris causes topographic deformation between centimetres to metres per year (Barsch, 1992). Monitoring rock glaciers is relevant to manage hazards resulting from, for example, debris flows caused by rock glacier front failure (Kofler et al., 2021).

The rock glacier Äußeres Hochebenkar is being monitored with terrestrial laser scanning since 2015 (Zahs et al., 2019). Both the M3C2 and the CD-PB M3C2 have been successfully applied to extract surface change information from multitemporal terrestrial laser scanning point clouds at this site (Zahs et al., 2019, 2022). Multitemporal point clouds originating from both UAV-borne photogrammetry and laser scanning have now been acquired at this rock glacier for the first time. The capability of quantifying 3D surface change based on point clouds originating from these acquisition strategies is, thus, yet to be investigated.

In our study we use point clouds obtained from UAV-borne laser scanning (ULS), UAV-borne photogrammetry using dense image matching (DIM), and terrestrial laser scanning (TLS). Point clouds were acquired on 30 August 2019 and 12 August 2021 in the lower tongue area of the rock glacier.

2.1 UAV-borne laser scanning data

UAV-borne laser scanning data were collected using a RIEGL VUX-1LR laser scanner mounted on a RIEGL RiCOPTER with an Applanix AP20 Inertial Measurement Unit (IMU) on board. Data acquisition was carried out with a strip spacing of 90 m and a mean flight altitude of 105 m above ground level (AGL) at a horizontal speed of 6 m/s. An angular resolution of 0.0476° and a pulse repetition rate of 820 kHz resulted in a point cloud with 63 million (2019) and 98 million (2021) points. The average point spacing is 0.06 m (2019) and 0.04 m (2021). In 2021, a higher point density was achieved by carrying out an additional overlapping flight with the same acquisition parameters (Figure 1 (b)). Postprocessing included estimation of the trajectory using differential GNSS and IMU data, resulting in georeferenced point clouds and trajectories. Furthermore, a fine alignment of the single flight strips was carried out[1].

2.2 UAV-borne Photogrammetry Data

Images for the DIM point cloud were acquired with a DJI Phantom 4 RTK equipped with a 1” CMOS 20 MP camera mounted on a gimbal. We used a strip spacing of 40 m at a constant flight altitude of 85 m AGL (Figure 1 (b)).[2]. The UAV flew with a horizontal flight speed of 4 m/s, taking nadir images every 6 seconds. A smaller number of oblique images were additionally acquired to strengthen the bundle block. Postprocessing included the georeferencing of the camera positions with PPK trajectory data as well as ten GNSS-measured Ground Control Points and dense image matching[3]. The obtained point cloud contains around 98 million points and has an average point spacing of 0.05 m.

2.3 Terrestrial Laser Scanning Data

Terrestrial laser scanning was performed from the same seven scan positions (Figure 1 (a), (b)) to obtain sufficient coverage of the study area. The same positions were used in both epochs. A Riegl VZ-2000i terrestrial laser scanner was used for data acquisition setting a vertical and horizontal angular resolution of 0.017°. The resulting point clouds features ca. 222 million points at an average point spacing of 0.03 m.

2.4 Data Processing

The ULS, DIM and TLS point clouds of both epochs were aligned to a georeferenced reference TLS epoch of 2019 (cf. Zahs et al., 2022) using an iterative closest point algorithm (ICP; Besl and McKay, 1992) in stable surfaces outside the rock glacier. We assess the alignment accuracy (Table 1) between point clouds of all epochs by calculating the standard deviation of M3C2 distances on stable rock walls distributed around the rock glacier (Zahs et al., 2022).

[1] Post processing was performed in the Software Applanix POSPac MMS 8 (Applanix, 2018) and RiProcess and RiPrecision (RIEGL Laser Measurement Systems GmbH, 2021, version 1.4.2)

[2] Flights were planned and carried out with the open source QGIS plugin PhotoPhly (PhotoPhly, 2022)

[3] Post processing was performed in the Software RTKLIB (RTKLIB, 2021, version 2.4.3) and Agisoft Metashape (Agisoft, 2021, version 1.8.2)

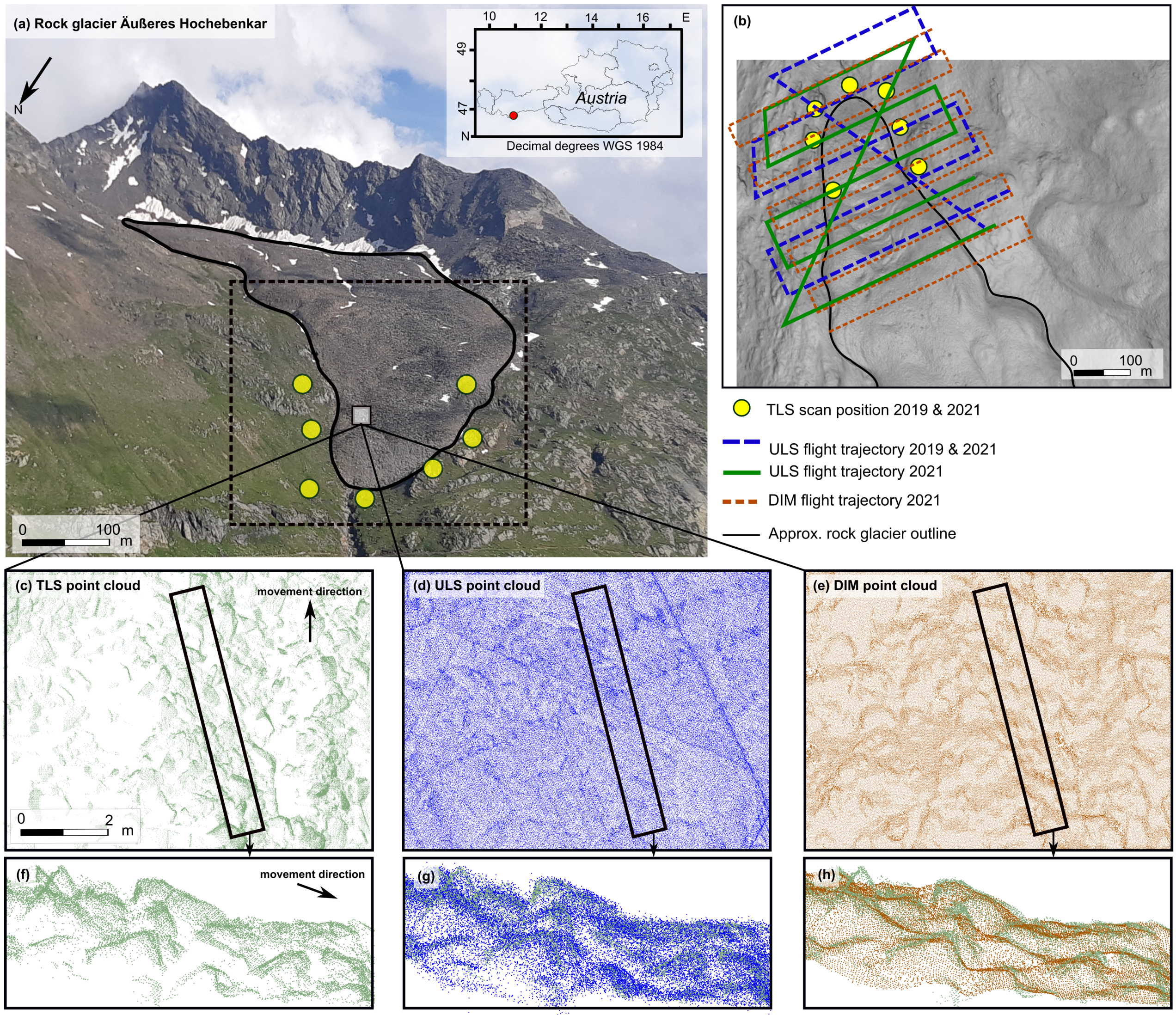

Figure 1. Overview map of the study site in the lower tongue area of the rock glacier Äußeres Hochebenkar, Austria. (a) View of the entire rock glacier from opposite site of the valley and locations of terrestrial laser scanning (TLS) scan positions (photo taken in 2020). (b) UAV flight trajectories and TLS scan positions shown on top of a hillshade derived from airborne laser scanning data. (c)-(e) Sampling of the rock glacier surface by point clouds originating from terrestrial laser scanning (TLS, (c)), UAV-borne laser scanning (ULS (d)) and UAV-borne photogrammetry using dense image matching (DIM, (e)) in a subarea of the rock glacier. (f)-(h): Close-up view showing differences in the geometric representation of the surface by TLS, ULS, and DIM point clouds. Smoothing effects introduced during dense image matching are visible in (h).

Compared datasets	Alignment accuracy [m]
ULS-ULS	0.021
ULS-DIM	0.052
TLS-TLS	0.011

Table 1. Alignment accuracies between compared point clouds from UAV-borne laser scanning (ULS), UAV-borne photogrammetry using dense image matching (DIM), and terrestrial laser scanning (TLS). Alignment accuracies were derived as standard deviation of M3C2 distances in stable areas between point clouds of two epochs.

3. METHODS

We perform pairwise 3D topographic change analysis using point clouds of different acquisition strategies (ULS-ULS, ULS-DIM and TLS-TLS) as input. Surface change and the associated LoDetection are quantified with the M3C2 and the CD-PB M3C2 algorithms. ULS-ULS and ULS-DIM comparisons using both methods, respectively, are evaluated against the TLS-TLS reference regarding their performance in (1) achieving high spatial coverage of derived changes, (2) accurately quantifying magnitudes and uncertainty of change, and (3) detecting significant change (change magnitudes > associated uncertainty).

3.1 Quantification of surface change

We quantify change using M3C2 distance calculation on all pairs of point cloud datasets (ULS-ULS, ULS-DIM, TLS-TLS).

Parameter	ULS & DIM	TLS (Iteration 1/2)
Min. no. pts. per segm.	30	400/50
Max. pt.-to-plane dist. of cand. points along plane normal [m]	0.2	0.1/0.2
Max. pt.-to-plane dist. of cand. point [m]	0.05	0.05/0.05
Max. angle between pt. normal vect. and cand. pt. plane [°]	5.0	5.0/5.0
Max. val. for roughness [m]	0.08	0.06/0.08
Max. val. for surface variation	0.06	0.05/0.06

Table 2. Segmentation parameters used to extract planar areas from UAV-borne laser scanning (ULS), UAV-borne photogrammetry using dense image matching (DIM), and terrestrial laser scanning (TLS) point clouds. A second iteration is applied to TLS point clouds to increase the spatial coverage of segmented planes by using less strict parameter settings. Due to a more uniform point spacing, only one iteration of segmentation was applied to ULS and DIM point clouds.

For each pair, we compute M3C2 distances between two point clouds at so-called core points. These core points (ca. 39 million points) represent a subset of the ULS 2019 point cloud and are distributed uniformly (point spacing 0.05 m) over the lower tongue area of the rock glacier (Figure 1). Using the exact same core points as input for all pairwise change computations ensures that change analysis results of M3C2 are comparable. While change is quantified for core points, the full information of the compared point clouds is used for estimation of magnitudes of change and the associated LoDetection. For all M3C2 change analyses we use the same parameters (cf. Lague et al., 2013) fitting the characteristics of the point clouds (projection scale: 1.0 m; normal scale: $\geq$ 8.0 m $\leq$ 15 m; maximum cylinder depth: 10.0 m; Zahs et al., 2019).

To reduce the uncertainty of quantified change the CD-PB M3C2 quantifies M3C2 distances between homologous planar areas in two epochs. Planar areas are extracted in each point cloud through seeded region growing segmentation. Based on findings in Zahs et al. (2022) we use rather strict parameter settings for the extraction of planar surfaces (Table 2) which was shown to present a good compromise between the resulting LoDetection and the spatial coverage of change analysis at the investigated site. Next, correspondences between planes in two different epochs are found using a binary random forest classifier. Three separate random forest classifiers (TLS-TLS, ULS-ULS, ULS-DIM) were trained with training data of corresponding and non-corresponding planes extracted from the compared point clouds. The overall accuracy of all three classifiers ranges between 0.92 and 0.94 (F1 score: 0.95 – 0.96; precision: 0.94 – 0.96; sensitivity: 0.93 – 0.94, specificity: 0.91 – 0.92) which was also confirmed by a visual evaluation of corresponding planes at different locations on the rock glacier.

3.2 Evaluation of resulting surface changes

We evaluate results of ULS-ULS-based and ULS-DIM-based change analysis with respect to the following aspects:

1. Spatial coverage: For M3C2, spatial coverage is interpreted visually and in terms of the difference in the number of core points for which enough points ($>$ 5) were available in both point clouds to compute M3C2 distances. As CD-PB M3C2 is not designed to perform change analysis with full spatial coverage, we quantify spatial coverage of this method based on the number of extracted planes in the first epoch t_1 that are assigned a corresponding plane in the second epoch t_2 as these plane pairs are used in the change analysis. Results, thus, express a relative spatial coverage.

2. Difference in the LoDetection: For M3C2, differences in the LoDetection are assessed by quantifying the absolute differences of the LoDetection at each core point to the TLS-TLS reference. For CD-PB M3C2, LoDetection differences are determined by deriving the absolute difference between the LoDetection of a TLS-TLS plane pair and the LoDetection of its closest (max. distance: 0.1 m) plane pair in ULS-ULS or ULS-DIM change analysis.

3. Accuracy of derived magnitudes of change: The accuracy of quantified magnitudes of change are evaluated at each core point by calculating the absolute difference to the TLS-TLS reference for M3C2. For CD-PB M3C2, the accuracy is evaluated in terms of the difference of change magnitude between a TLS-TLS plane pair and its closest (max. distance: 0.1 m) plane pair in ULS-ULS or ULS-DIM change analysis.

4. Detection agreement: Agreement of significant change or non-significant change at core points (M3C2) or planes in point cloud of t_1 (CD-PB M3C2) with the TLS-TLS reference. Significant change or no significant change derived from both ULS-ULS change computation and the TLS-TLS reference is considered as agreement (true positive or true negative), whereas significant change derived only in the ULS-ULS change analysis is considered as disagreement (false positive). Similarly, change derived as non-significant in the ULS-ULS change analysis and as significant in the TLS-TLS reference is considered as disagreement (false negative). The same applies for ULS-DIM change analysis.

4. RESULTS

4.1 Spatial coverage of change analysis

Spatial coverage achieved with M3C2 using TLS, ULS and DIM point clouds as input is visualised in Figure 2 (a) - (c). M3C2-based change analysis with ULS-ULS and ULS-DIM point clouds allows change quantification for $>$ 99% of the core points as a result of the top-down perspective of UAV-borne acquisitions. As core points are distributed uniformly in the lower tongue area of the rock glacier (cf. section 3) we consider the percentage share of core points to represent the spatial coverage of the lower tongue area in the remainder of this paper. In contrast, TLS-TLS-based change analysis derives change in only 38.67% of this area and is strongly affected by occlusion effects due to high variations of the surface topography and the limited field of view of ground-based acquisitions (Figure 1). This clearly shows the advantage of UAV-derived point clouds compared to ground-based data for the complex topography of the rock glacier.

Spatial coverage of plane pairs used in change analysis of CD-PB M3C2 with TLS, ULS and DIM point clouds as input is shown in Figure 3 (a) - (c). For CD-PB M3C2, between 72.97% (ULS-DIM) and 75.79% (ULS-ULS) of planes extracted in t_1

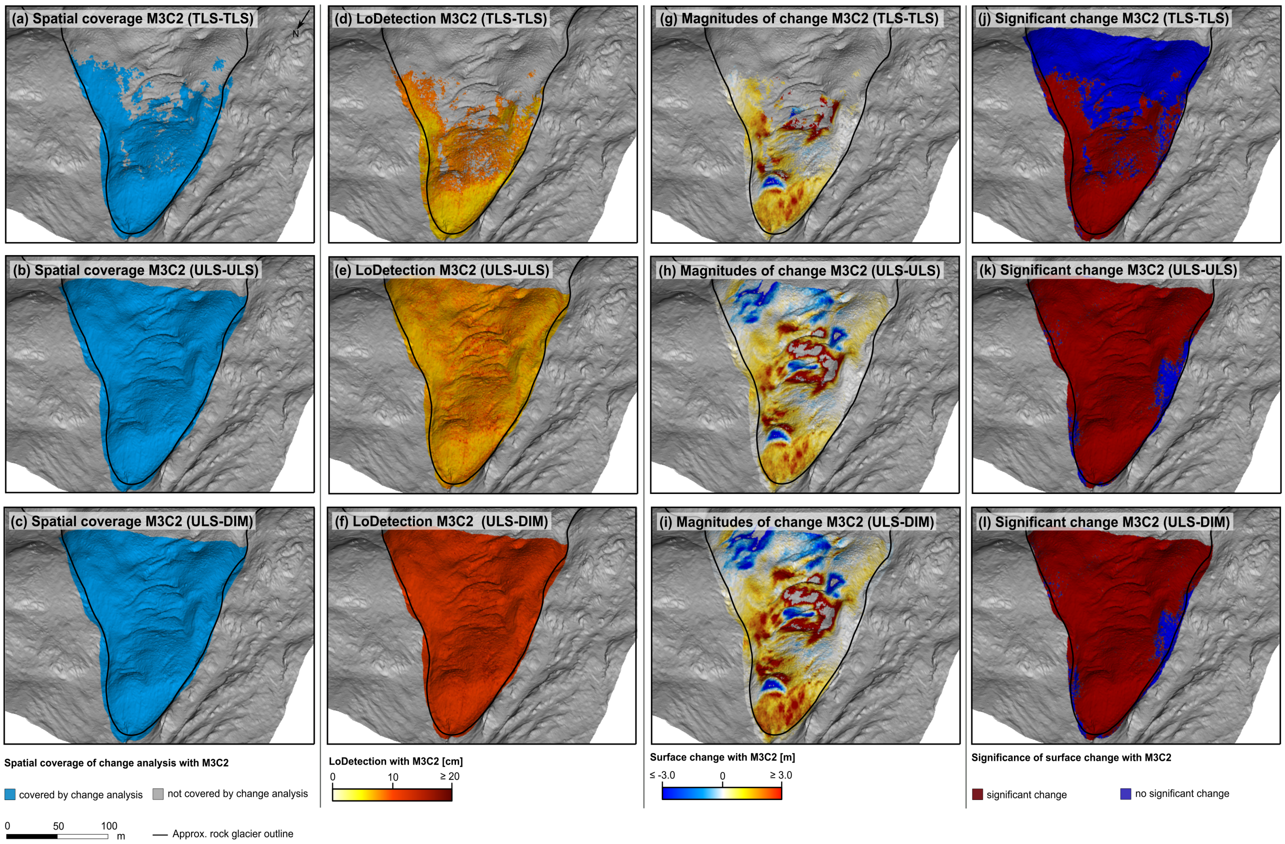

Figure 2. Results of M3C2-based change analysis using point clouds derived from terrestrial laser scanning (TLS), UAV-borne laser scanning (ULS), and UAV-borne photogrammetry using dense image matching (DIM) as input. Spatial coverage (a) - (c), LoDetection (d) - (f), magnitudes of surface change (g) - (i), and significance of surface change (j) - (l) are shown on top of a hillshade derived from airborne laser scanning data.

were assigned a reference plane in respective t_2. For the TLS-TLS reference, only 56.40% of planes in t_1 were assigned a reference plane in t_2. This corresponds to 6.84% (TLS-TLS), 13.22% (ULS-ULS), and 14.78% (ULS-DIM) of corepoints used in the M3C2 change analysis covered by CD-PB M3C2 change analysis. While the total number of plane pairs is much higher for the TLS-TLS reference (276,308) compared to both ULS-ULS (121,786) and ULS-DIM (117,253), the spatial distribution of plane pairs is more uniform for ULS-ULS and ULS-DIM change analysis. These differences in spatial distribution and absolute number of plane pairs can be attributed to lower point counts but more uniform point distributions in the UAV-based point clouds.

4.2 Level of Detection of change analysis

LoDetection values for M3C2 are shown in Figure 2 (d) - (f). For M3C2, the LoDetection is lowest for TLS-TLS change analysis (mean: 0.08 m; std. dev.: 0.02 m), followed by ULS-ULS change analysis (mean: 0.11 m; std. dev.: 0.01 m) and highest for ULS-DIM change analysis (mean: 0.19 m; std. dev.: 0.02 m). Large differences for both UAV-based change analyses can be attributed to lower alignment accuracies between the point cloud pairs compared to the TLS-TLS reference. Higher LoDetection values also reflect influences of lower point densities of the DIM point cloud.

LoDetection values for CD-PB M3C2 are provided in Figure 3 (d) - (f). CD-PB M3C2-based change analysis derives lowest LoDetection values for the TLS-TLS change analysis (mean: 0.02 m; std. dev.: 0.01 m), followed by ULS-ULS change analysis (mean: 0.03 m; std. dev.: 0.01 m) and highest for ULS-DIM change analysis (mean: 0.06 m; std. dev.: 0.01 m). The mean difference of ULS-ULS LoDetection values and the TLS-TLS reference amounts to +0.01 m (std. dev.: 0.01 m). For ULS-DIM change analysis, LoDetection differs by +0.05 m on average (std. dev.: 0.01 m). Differences are interpreted as results of lower alignment accuracies for ULS-ULS (0.02 m) and ULS-DIM point clouds (0.05 m), which are directly propagated into a higher LoDetection. Since the CD-PB M3C2 estimates the LoDetection on locally planar surfaces, different sampling of the surface in ULS and DIM point clouds compared to TLS point clouds does not notably affect the LoDetection.

4.3 Magnitudes of surface change

Magnitudes of surface change for M3C2 are visualised in Figure 2 (g) - (i). Mean positive M3C2-based change magnitudes range between 1.39 m and 1.52 m (std. dev.: 0.85 m – 0.93 m) and mean negative change magnitudes range between -1.18 m and -1.33 m (std. dev.: 0.62 m – 0.89 m) for all three pairs of datasets. ULS-ULS change analysis achieves magnitudes of change close to magnitudes derived from TLS-TLS change analysis. Mean absolute differences in change magnitudes amount to 0.04 m (std. dev.: 0.05 m). Magnitudes of change derived from ULS-DIM analysis (mean: 0.12 m; std. dev.: 0.08 m) show higher differences to magnitudes derived from the TLS-TLS reference. Generally, differences in magnitudes are attrib-

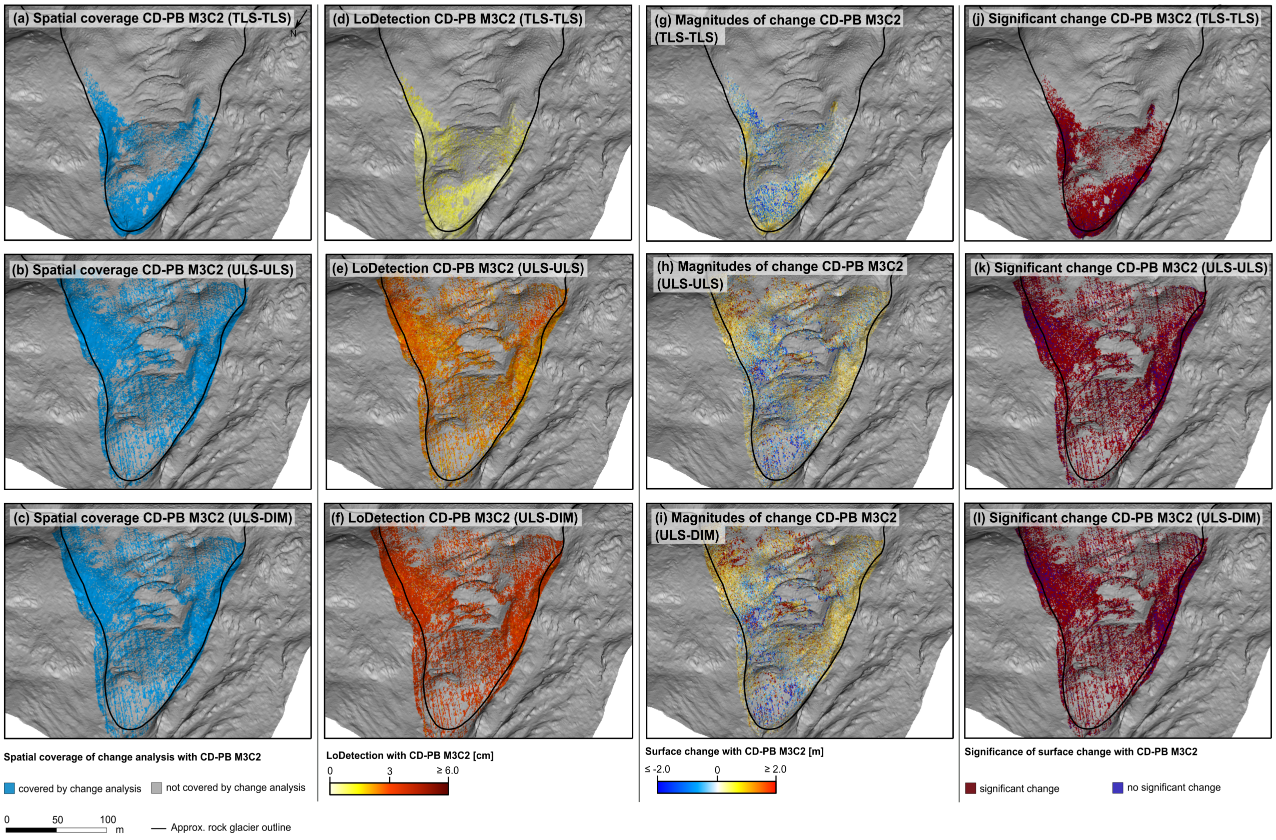

Figure 3. Results of CD-PB M3C2-based change analysis using point clouds derived from terrestrial laser scanning (TLS), UAV-borne laser scanning (ULS), and UAV-borne photogrammetry using dense image matching (DIM) as input. Spatial coverage (a) - (c), LoDetection (d) - (f), magnitudes of surface change (g) - (i), and significance of surface change (j) - (l) are shown on top of a hillshade derived from airborne laser scanning data.

uted to lower alignment accuracies between ULS-ULS point clouds and ULS-DIM point clouds. Moreover, differences are also considered as results of a less accurate geometric representation of the surface by ULS and DIM point clouds and also smoothing during DIM point cloud generation in dense image matching (Figure 1 (g), (h)). This then leads to differences in the estimation of local point cloud positions in the process of M3C2 distance calculation.

Magnitudes of surface change for CD-PB M3C2 are visualised in Figure 3 (g) - (i). For CD-PB M3C2, mean positive change magnitudes range between 0.84 m and 0.69 m (std. dev.: 0.58 m – 0.63 m) and mean negative change magnitudes range between -0.82 m and -0.97 m (std. dev.: 0.43 m – 0.52 m) for the three pairs of datasets. Absolute differences in magnitudes compared to the TLS-TLS reference are relatively small for both ULS-ULS (mean: 0.02 m; std. dev.: 0.01 m) and ULS-DIM change analysis (mean: 0.06 m; std. dev.: 0.01 m) and mostly reflect lower alignment accuracies. We do not assume effects of less accurate geometric representation of the surface or lower positional accuracies to influence resulting change magnitudes because CD-PB M3C2 ensures that change is computed on homologous planar areas only.

4.4 Accuracy of change detection

Significant change detected with M3C2 are shown in Figure 2 (j) - (l). M3C2 derives significant change in 82% – 89% of the area of change analysis, whereas CD-PB M3C2 derives significant change in 89% – 90% of the area. Despite higher LoDetection values resulting from ULS-ULS and ULS-DIM change analysis compared to TLS-TLS change analysis, magnitudes of change derived for the two-year-timespan do largely not fall below their associated LoDetection, thereby yielding significant changes for confident change detection.

Comp. datasets	Spat. cov.	Uncert.	Agr. of change magn.	Det. acc.
ULS-ULS (M3C2)	+	0	+	+
ULS-DIM (M3C2)	+	-	-	-
TLS-TLS (M3C2)	-	+	N/A	N/A
ULS-ULS (CD-PB M3C2)	+	0	+	+
ULS-DIM (CD-PB M3C2)	+	-	-	-
TLS-TLS (CD-PB M3C2)	-	+	N/A	N/A

Table 3. Performance of biennial change analysis at a rock glacier with M3C2 and CD-PB M3C2 using point cloud pairs originating from UAV-borne laser scanning (ULS), UAV-borne photogrammetry using dense image matching (DIM), and terrestrial laser scanning (TLS) as input. Performance (+: best; 0: medium; -: worst of the two/three options) is evaluated with respect to spatial coverage, uncertainty of quantified change, the accuracy of change magnitudes and change detection compared to the TLS-TLS reference.

Significant change detected with CD-PB M3C2 are shown in Figure 3 (j) - (l). Significant and non-significant change detected in TLS-TLS-based change analysis was also detected in ULS-ULS change analysis in 87% of the area covered by plane pairs (77% true positive, 10% true negative, 7% false positive, 6% false negative). For ULS-DIM change analysis, 85% of significant and non-significant change between plane pairs detected in TLS-TLS change analysis was correctly detected (75% true positive, 10% true negative, 6% false positive, 9% false negative). A qualitative summary of the evaluation of ULS, DIM and TLS point clouds as input for biennial 3D change analysis with M3C2 and CD-PB M3C2 at the monitored rock glacier is provided in Table 3.

5. DISCUSSION

5.1 Implications for 3D/4D monitoring of surface change

When using ULS and DIM point clouds as input for 3D topographic change analysis on an active rock glacier, change analysis can benefit from larger and more uniform spatial coverage compared to TLS point clouds. Moreover, individual objects (i.e. boulders on a rock glacier) are represented more completely (i.e. multiple faces of a boulder) due to the top-down view of UAV-based acquisition. This becomes especially relevant where, for example, movement takes place parallel to the general orientation of the surface. A more complete coverage of the surface through UAV-borne acquisitions might then enable change quantification in areas where TLS-TLS change quantification is not possible. Geographic interpretation of change derived from ULS and DIM point clouds is, thus, possible in almost the entire target area and less change information might be missed due to occlusion or missing spatial overlap between two epochs.

Change analysis based on all UAV-derived point clouds results in higher LoDetection values associated with the quantified changes due to lower point density, lower positional accuracy, and resulting lower alignment accuracies between the two epochs. Moreover, visually recognisable smoothing effects (Figure 1) introduced during point cloud reconstruction with dense image matching results in a less accurate geometric representation of objects in DIM point clouds, which also influences the resulting LoDetection. Despite higher LoDetection values, magnitudes of change derived from ULS-ULS and ULS-DIM change analysis in our study mostly exceeded the associated LoDetection. Hence, due to the relatively high biennially change rates at the rock glacier, significant change could be derived in large parts of the target area and the analysis was hardly affected by slightly higher LoDetection. This is also reflected in higher agreement with TLS-TLS change analysis with respect to the distinction of significant from non-significant change both for ULS-ULS and ULS-DIM change analysis. The benefit of lower LoDetection values achieved with TLS-TLS change analysis is, therefore, considered most relevant for applications where magnitudes of surface change are close to the LoDetection. For active rock glaciers this is expected for shorter (e.g., sub-monthly) monitoring intervals, where actual change magnitudes are in the order of only a few centimetres and, thus, close to or below the associated LoDetection (Ulrich et al., 2021). In such set-ups change analysis can benefit from acquisitions of TLS point clouds.

Change magnitudes derived from ULS-based change analysis are close to change magnitudes derived from TLS-based change analysis with both M3C2 and CD-PB M3C2 (mean absolute difference: 0.03 m – 0.04 m). Using DIM point clouds as input, magnitudes deviate more from TLS-based change analysis (mean absolute difference: 0.11 m – 0.12 m). The required accuracy of change magnitudes is specific to the respective use case and application. Generally, applications that require accurate change magnitudes should therefore prefer TLS over ULS point clouds over DIM point clouds as input.

ULS and DIM point clouds provide valuable input for biennial 3D topographic change analysis at an active rock glacier. We expect this also for higher-frequent monitoring (yearly or monthly) as long as the accuracy is fullfilling the application requirements and the magnitudes of quantified change exceed the associated LoDetection at the applied frequency of monitoring. In contrast, the benefit of applying additional TLS-based change analysis is assumed to be limited due to the already low LoDetection values achieved by ULS-ULS-based change analysis. These findings allow the selection or combination of 3D close-range sensing techniques and methods of 3D change analysis which are most appropriate for a specific use case and application, depending on the acceptable uncertainty, accuracy of change quantification or required spatial coverage. Findings of our study, thereby, support the theoretical and practical design of future measurement setups for repeat monitoring of rock glaciers and other natural scenes with similar surface characteristics (e.g., landslides or debris covered glaciers). Further investigations are required with respect to the performance of ULS-based and DIM-based change analysis in case of high-frequency (hourly to monthly) monitoring when change magnitudes tend to decrease and the quantification of change with low uncertainty becomes especially relevant (Kromer et al., 2017). Additionally, the potential of ULS and DIM point clouds is to be investigated for 4D change analysis methods, which make use of the full temporal information of point cloud time series (Kromer et al., 2017; Anders et al., 2021; Winiwarter et al., 2022) and for multi-modal point clouds in integrated 4D workflows.

6. CONCLUSION

We investigated the potential of point clouds originating from UAV-borne photogrammetry using dense image matching (DIM) and UAV-borne laser scanning (ULS) as input for 3D topographic change analysis. We therefore evaluated results of biennially change analysis at an active rock glacier compared to a TLS reference change analysis using two state-of-the-art methods for 3D change analysis (M3C2, CD-PB M3C2). Our study shows the improved spatial coverage of M3C2 achieved with point clouds acquired with UAVs (+60% of core points used for change analysis). For CD-PB M3C2, ULS and DIM point clouds enabled a spatially more uniform distribution of plane pairs used for change quantification and a slightly higher spatial coverage (+6% (ULS-ULS) – +7% (ULS-DIM) of core points used for change analysis) compared to the TLS reference. Magnitudes of M3C2 change were closer to the TLS reference for ULS-ULS (mean difference: 0.04 m; std. dev.: 0.05 m) compared to ULS-DIM (mean difference: 0.12 m; std. dev.: 0.08 m). Similar results were obtained for CD-PB M3C2 using ULS-ULS (mean difference: 0.02 m; std. dev.: 0.01 m) and ULS-DIM (mean difference: 0.06 m; std. dev.: 0.01 m). Moreover, magnitudes of change were above the associated uncertainty in 82% – 89% (M3C2) and 89% – 90% (CD-PB M3C2) of the area of change analysis.

Our findings demonstrate the potential of ULS and DIM point clouds as input for accurate 3D topographic change analysis for the study at hand. Different applications, for example using more frequent monitoring, might have different requirements with respect to spatial coverage or the acceptable uncertainty and accuracy of change quantification and might therefore need a different setup that fits the purpose of the analysis.

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