GLACIER VELOCITY DETERMINATION FROM MULTI TEMPORAL TERRESTRIAL LONG RANGE LASER SCANNER POINT CLOUDS

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ABSTRACT:

Research on the motion behaviour of arctic glaciers provides important information about the influence of global temperature changes on the climate system and especially the global sea level rise. In the past years dramatic changes could be observed for some of the Greenland outlet glaciers. Jacobshavn Isbrae is one of the fastest and most productive glaciers in Greenland and is therefore an interesting research object. The paper presents a new technique for the determination of 3D glacier surface velocity fields, which is based on processing multi-temporal terrestrial long range laser scanner data. Multi-temporal 3D point clouds were acquired by a long range terrestrial laser scanner Riegl LPM-321, which offers a maximum range of 4 km when measuring on glacier ice. Velocity vectors are determined by applying 2D matching techniques to the point clouds interpolated to a regular grid. The paper also proposes solutions for the determination and elimination of angular errors which occurred in the data. The results show that terrestrial long range laser scanning is a suitable tool for the determination of high-resolution velocity fields of glaciers.

1. INTRODUCTION

The impact of global temperature changes becomes most clearly evident in the polar regions of the earth. Recent changes in glacier front retreat, elevation and flow velocity of glaciers along the margins of the Greenland Ice Sheet are important indicators for climate change. During the last years, a strong increase of the flow velocity has been observed for some Greenland outlet glaciers, which means a stronger contribution to the global sea level increase. Among those glaciers, Jacobshavn Isbrae is one of the fastest and the most productive (Echelmeyer et al., 1992), contributing 4% of the annual see level rise (Joughin et al., 2004). First velocity measurements at its glacier tongue have been conducted by (Hammer, 1893) and (Engell, 1904) at the beginning of the 20th century. The determined velocities of about 20 meter per day could still be proven by (Carbonell/Bauer 1968). In the past decade, however, the behaviour of the glacier tongue changed dramatically. The glacier front has retreated by almost 15 km between 2001 and 2007 and the velocity has almost doubled.

In this context, the goal of the research work presented here was to determine spatio-temporal velocity fields at the glacier tongue of Jacobshavn Isbrae using photogrammetric methods. In 2004, a measurement campaign has been conducted in order to determine the glaciers movement characteristics using image sequence analysis (Maas et al., 2006). Velocities up to 40 m/d could be observed. In a second campaign in 2007, multi-temporal terrestrial laser scanner data were acquired in addition to the high-resolution terrestrial image sequences with the goal of determining glacier surface velocity fields. Section 2 briefly presents the instrument. Section 3 characterizes the 3D point cloud data. In section 4, a cross correlation technique for the determination of glacier surface velocity vectors is developed.

Section 5 addresses some specific technical problems and develops a scheme for correcting timing and angular reference effects on the data. Section 6 shows glacier surface velocity fields obtained from the method.

2. DATA ACQUISITION

2.1 Long Range Terrestrial Laser Scanner

For data acquisition, a prototype of a long range terrestrial laser profile measurement system Riegl LPM-321 (figure 1) has been used. The scanner is specified with a maximum range of 6 km and achieved up to 4 km on glacier ice. The range turned out to be affected by the suns position, with a reduced maximum range when measuring on sun-lit surfaces. This had to be taken into account setting up the schedule for sequence measurements and during data processing.

Figure 1. Riegl LPM-321 at Jacobshavn Isbrae

The maximum range of 4 km can only be obtained at a rather slow measurement rate of only 10 points per second. This is

connected with long scanning times and critical power supply requirements. Power supply in the field camp was realised using a combination of dry batteries and solar panels when the weather was sunny and a power aggregate otherwise.

2.2 Observation and Datasets

The ice stream was observed from a hill in a distance of 1.6 ... 4 km. This means that the main ice stream up to a width of 2.5 km could be scanned. Because of the large distances, the scan resolution was chosen as fine as possible. A complete scan, which covers the whole visible glacier stream within a radius of 4 km in a sector of 30°, was recorded with a resolution of 0.027° in two epochs. Additionally, smaller windows of glacier parts, which were of special interest, were scanned with the finest resolution of 0.018°. Sequences with up to 5 scans are available for these details. Each scan was georeferenced through retro reflecting targets, which were measured by tachymeter and integrated into a local geodetic network. This paper concentrates on the complete scan of the glacier tongue which consists of two scan epochs.

3. DATA SET

In the following, the most important characteristics of the laser scanner data sequence are outlined. They are of substantial importance for the development of an adequate method for velocity field determination.

3.1 Scan distribution

In order to enable maximum range and to scan with high resolution, rather long scan times had to be accepted. To protect the scanner from wind, it was placed in the lee of a rock. The position allowed for a horizontal field of view of about 30°. To avoid a loss of data because of power outage during the long scan times, each scan had to be divided into smaller sectors, which were scanned successively (see figure 2).

While the scan of epoch 1 consists of three partial scans, the scan of epoch 2 consists of twelve partial scans due to some power supply difficulties, which could not be fixed in the field camp. All partial scans of both epochs have been recorded from the same scan position and refer to the same coordinate system.
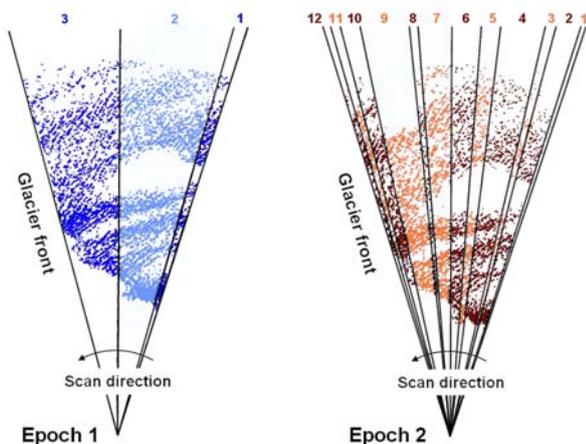

Figure 2: Contribution of single scans to the laser scanner datasets of both epochs

3.2 Scan times

The glacier tongue was scanned at two epochs, with each scan lasting about 8 hours. Figure 3 shows the individual time behaviour of the scans as well as time differences between both epochs. The measurement time per horizontal angle interval can vary from scan to scan due to different vertical fields of view. This leads to different time differences between the scans of both epochs. Breaks of a few minutes up to 20 minutes may exist between successive scans.
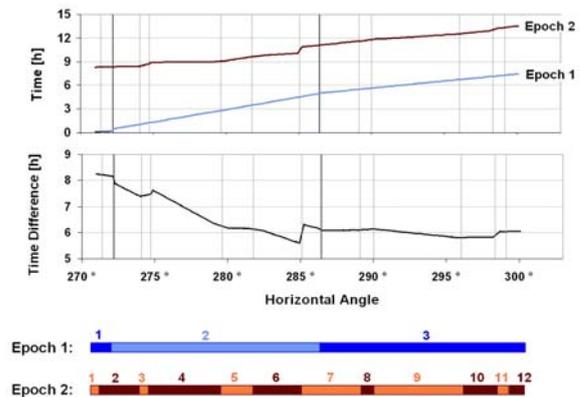

Figure 3: Time behaviour of the scans of both epochs

3.3 Surface structure of the glacier tongue

The surface of the glacier tongue is extremely rugged and traversed by numerous deep crevasses. They separate single ice formations with dimensions of tens of meters from each other, which form good features for measurement purposes. Due to the fact that the glacier tongue was scanned from a hill, many laser points hit the glacier surface at acute angles of incidence. Therefore sloped flanks of the ice structures oriented towards the laser scanner were densely covered with points, whereas scan shadows appeared at the back side of the ice formations. As a consequence, single structures can be clearly delineated from each other in the XY-projection of the laser scanner data. Figure 4 shows an overlay of the laser scanner data of two scan epochs.
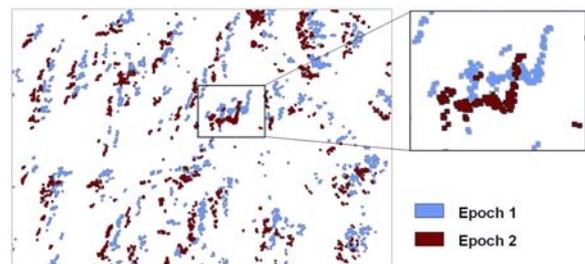

Figure 4: Scanned structures of the glacier at two epochs

It can be seen that the structures changed their position and that corresponding structures can clearly be recognized in the two measurement epochs. The observation angle for an ice formation is almost the same at both scan epochs because the translation is small in comparison to the distance between scanner and glacier. A noticeable effect, which occurs between two scan epochs, is a different number of points that represent the same structure. The reason could be the different position of the sun at both epochs because this influences the signal-to-noise ration in the echo detection of reflected laser pulses (see section 2.1).

4. METHOD

Besides information on the surface structure and the front height, information on absolute velocity values and on local velocity variations in the area of the glacier tongue can be derived from multi-temporal laser scanner data, taken in short time intervals. While absolute velocities are necessary to obtain knowledge on long term changes of the glaciers flow behaviour, relative velocities within the scanned area may provide information about the physical properties of the glacier and its underground. Thus the aim is to develop an appropriate method which allows for the determination of the glacier tongue velocity field from consecutive terrestrial laser scanner 3D point clouds. .

4.1 Basic idea

In the horizontal view of the laser scanner data clear structures are distinguishable. They can be used as features to be tracked between two scan epochs. So the basic idea is to project the laser scanner point clouds into the horizontal raster plane. The raster width is defined by the expected accuracy of the velocity field and limited by the lateral accuracy and the density of the scanned points. In this way raster images are generated where each pixel that contains a laser scanner point is filled with a grey value depending on the Z value of the point. For that purpose the partial scans of each epoch are merged to one scan, so that for each epoch one raster image can be created.

Glacier surface motion will result in shifts of patterns in the raster image. This allows for the application of established image analysis techniques for the determination of translation vector fields. The translation of glacier surface structures between the two epochs can be derived using 2D area based matching techniques. In a second step, the velocity values are calculated from the translation vectors considering the recording time of the laser scanner points.

4.2 Translation vector field determination

It is assumed that for a patch, which merely contains a small area of the glacier, only translations can be determined, but no rotations. Possible changes in scale between a patch of epoch 1 and 2 are also supposed to be too marginal to be detectable regarding to the existent time interval of the two scans. This allows to use a simple cross correlation technique for matching.

Depending on the size of the ice formations of the glacier and the point cluster of the raster images, the size of the patches is defined. In case of a high resolution of the scan images – in order to exploit the full accuracy potential of the data – the patches contain a lot of black pixels in relation to the number of pixel that represent laser scanner points. Black pixels are pixels without any information and do therefore not contribute to the cross correlation coefficient. This leads to very small values of the cross correlation coefficient which are not comparable and can hardly be used as a criteria to detect outliers. The low percentage of non-black pixels also leads to mismatches because the distribution of the laser points that forms a structure in epoch 1 and 2 is different. This means that some corresponding points do not meet each other while finding the best fit of the patches but meet black pixels and do therefore not contribute to the translation vector.

To increase the weight of pixels representing laser scanner points the image is morphological filtered. The structures are iteratively dilated to obtain a better ratio between black and non-black pixels. The dilation can be applied to the whole image or to each patch individually. The second option is more time consuming, but is better adapted to the characteristics of the data. Patches in lower distance to the scanner position contain denser points than patches in higher distance and require therefore less iterations of dilatation. Hence, the morphological filtering is iteratively applied on each patch until a certain ratio is obtained. If the number of iterations exceeds a certain threshold, the respective patch is not used because it does not contain enough information to perform a reliable matching (e.g. patches at the margins of the scan).

Figure 5 shows the colour coded motion field of the whole scan area as well as a smaller part of the scan with translation vectors. Discrepancies are visible in the motion field, which occur along the borders of neighbouring partial scans. Two reasons can be considered to explain this effect: The leaps in the results could be caused by longer time intervals between stop and start of adjacent partial scans (see section 3.2), or they could be caused by a horizontal angle displacement between two neighbouring scans.
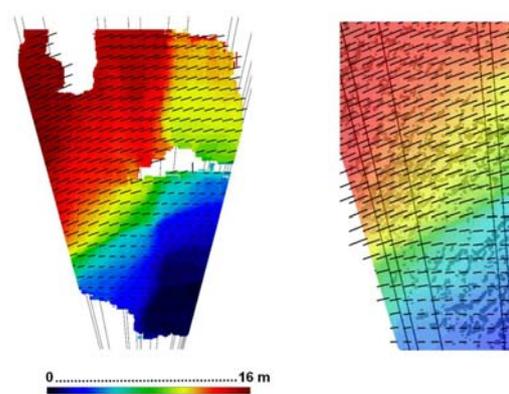

0 ·························· 16 m

Figure 5: Translation vector field

4.3 Velocity field determination

To determine velocities from the translation vector field for each patch of epoch 1 and its corresponding patch of epoch 2 an appropriate time stamp has to be assigned to the data. This is not trivial, as the laser scanner data is acquired sequentially at a rather low scan rata. Moreover, consecutive scans will not necessarily have identical scan windows, and they had to be divided into multiple partial scans for technical reasons (see section 3.2). In the dataset there is no individual time stamp for individual points. Solely start and stop time of each scan are recorded. To interpolate time between those points, two possibilities can be considered: Either time is linearly interpolated with respect to the scan angles of the points, or it is linearly interpolated referring to the points recording order. The second solution is better because the scan pattern is not entirely regular and the angular distance between two scan lines may slightly differ (Figure 6). Time interpolation by measurement order is possible because point IDs are logged even if points could not be measured (due to lack of reflectance).

After assigning a time to each scan point, it is still to investigate how the time for a patch has to be calculated. Again there are two possibilities: The time of the scan point which is nearest to the centre of the patch could be inherited for the patch, or the average time of all scan points within a patch could be calculated. The latter is the more reliable option because it takes into account the distribution of points within a patch.
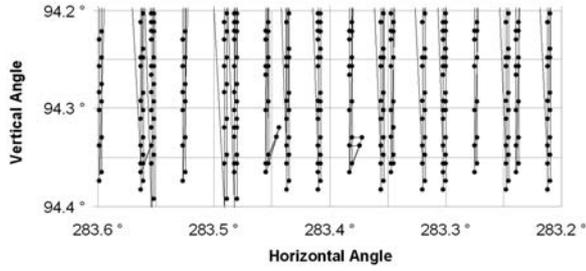
Figure 6: Scan pattern

Using the time stamp interpolation technique as described above, the velocity vector field was derived from the translation vector field (figure 7). Some of the leaps in figure 5 are slightly smoothed, but the most intense one is still clearly visible (black frame). This implies the assumption that the effects are caused by the influence of angular displacements between partial scans.

0 .... 16 m

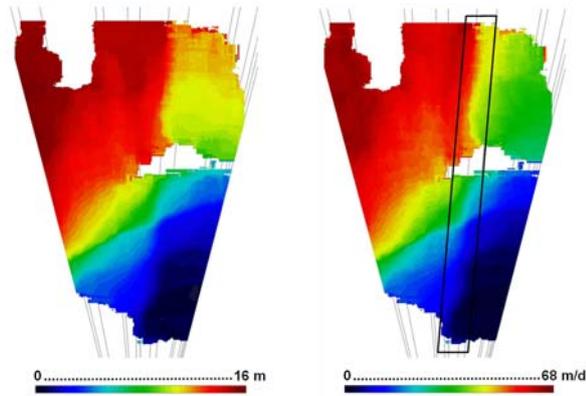0 .... 68 m/d

Figure 7: Translation field (left) and velocity field (right)

5. CORRECTION OF ANGULAR REFERENCE EFFECTS

Even small angular discrepancies between partial scans will clearly influences the processing of the scan data. The effect disturbs the results in two different ways: Firstly, the discrepancy occurs at the borders of the partial scans of each epoch affecting the predictions about local velocity variations. Secondly, if the discrepancy occurs between two epochs, it will have influence on predictions about absolute velocity values. Both effects have to be determined and corrected.

5.1 Angular discrepancies between partial scans

This effect affects the component of the translation vector perpendicular to the viewing direction, i.e. the glacier movement direction. The angular effect increases linearly with the distance and is transmitted to all subsequent scans. To determine the angle deviation it is assumed that the velocity of the glacier shows a high local correlation for neighbouring points in the same distance from the scanner position. Hence, each border between partial scans is analysed in the following way: Two adjacent scans which belong to one epoch (E_2S_1 and E_2S_2) are processed together with the scan of the other epoch (E_1S_0) that overlaps the border of the neighbouring scans. First all three scans are rotated around the Z-axis by the stop angle of the first partial scan (E_2S_1). In this way the border of the neighbouring scans (E_2S_1 and E_2S_2) lies on the X-axis, and the

Y-direction now completely includes the effect of the angular discrepancy. If a horizontal line of points is defined at both sides of the scan border of E_2S_1 and E_2S_2, the translation vectors for each line can be calculated involving scan E_1S_0 (figure 8).
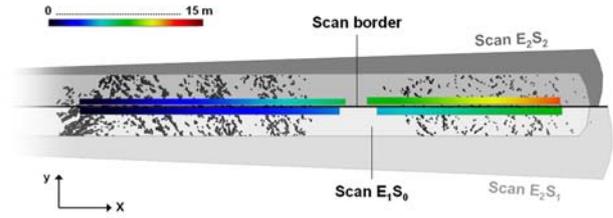

Figure 8: Colour coded y-component of the translation vectors at both sides of the border between partial scans of one epoch

Comparing the y-component of the translation vectors of neighbouring points (where one refers to scan E_2S_1 and one to scan E_2S_2), they should be nearly identical if no angular displacement exists. Though, it has to be taken into account that leaps in time between two scans show the same effect as angular displacements. Therefore, before comparing the translation vectors they have to be reduced by the effect caused by time differences. This is done by calculating the velocities of the neighbouring points from adjacent scans and assuming that the velocities are equal. This leads to the equation of the y-component of the translation vector of Scan E_2S_2 which is only influenced by time (equation 1)

$$v_1 = v_2 \qquad \rightarrow \qquad \frac{y_1}{t_1} = \frac{y'_2}{t_2} \qquad \rightarrow \qquad y'_2 = \frac{y_1}{t_1} \cdot t_2 \qquad (1)$$

where:
v_1, v_2 … velocities referring to scan E_2S_1 and E_2S_2
t_1, t_2 … recording times referring to scan E_2S_1 and E_2S_2
y_1, y_2 … y-component of the translation vector determined for scan E_2S_1 and E_2S_2
y'_2 … y-component of the translation vector of scan E_2S_2 only influenced by time

Thus, the difference between y'_2 and y_2 is caused by angular displacements whereas the difference between y'_2 and y_1 is caused by leaps in time. The difference between y_2 and y_1 includes both effects. To calculate the angular deviation, a line is fit into the difference values between y'2 and y2. Its slope defines the angle by which scan E2S2 and all the following scans have to be rotated to correct the angular discrepancy.

Figure 9 shows two examples of neighbouring scans with a leap in time (top) and an angular deviation (bottom) affecting the data.
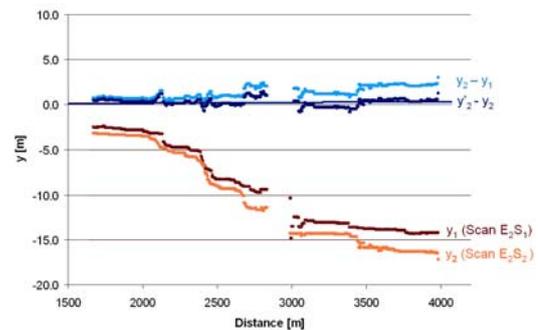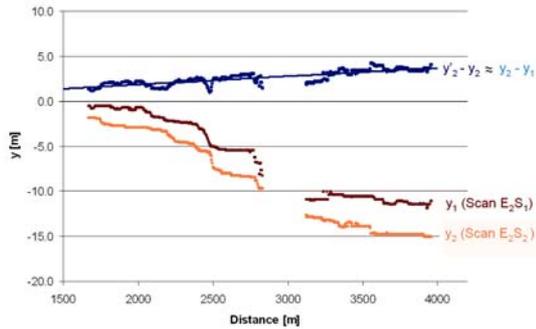
Figure 9: Examples of translation differences at the border of partial scans

5.2 Angular discrepancies between scans of two epochs

If angular effects occur between partial scans, it has to be assumed that an angular displacement can also occur between the corrected and merged scans of different epochs. The effect influences the absolute velocity values. The angular discrepancy can be calculated if stationary objects are available in the scans of both epochs. First, the apparent translation between epoch 1 and 2 of those objects has to be determined. The obtained translation vectors are perpendicular to the viewing direction. Then the angular discrepancy can be calculated considering the distance between laser scanner and static object. The larger the distance of the stationary objects to the laser scanner position, the more reliable the effect can be determined. Though, due to the dimensions of the glacier tongue of Jacobshavn Isbrae, fixed objects were only available in a distance up to 1500 m from the scanner. In this area, rock and 'dead ice' was scanned.

Figure 10 shows a comparison between the velocity field of the originally scanned data and the velocity field calculated after correcting for all determined angular effects. The maximum angular deviation occurred between scan 6 and 7 of epoch 2 and amounted 0.054°. This equates to lateral displacements of 1.4 m in a distance of 1500 m up to 3.7 m in a distance of 4000 m. Because the angle deviations between subsequent partial scans add up, even minor angular displacements may have much influence on the calculated velocities.
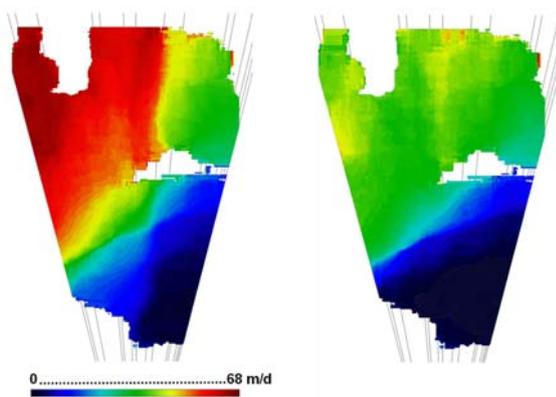

Figure 10: Velocity field calculated from uncorrected scans (left) and corrected scans (right)

5.3 Remaining effects

As one can see from figure 10, not all effects occurring along scan borders could be removed by applying the angular correction scheme. One reason for this is the fact that patches may overlap scan borders. If there is a leap in time between the two adjacent scans, the time value for the patch can not be calculated correctly and the matching result is less reliable. This also leads to a miscalculation of velocities. A second consideration is that patches in different distances to the laser scanner position cover different intervals of the horizontal angle. This means that the time difference within a patch in low distance is much larger than within a patch of the same size in high distance.

A solution could be not to raster the data by their x and y coordinates but to raster the data by their horizontal angle and the distance of the points (polar grid). This would facilitate a design for the velocity field raster wherein patches do not overlap scan borders, and it allows for patches of the same size independent on the distance.

6. RESULTS

As shown in figure 10, the consideration of angular discrepancies is very important. Since the rotation of the scanner is anti-clockwise, the largest influence of the angular deviations will be at the left margin of the data set close to the glacier front. Velocity corrections here are up to 20 m/d, which is 50% of the estimated velocity. This means that the correction of the angular effects is of vital importance.
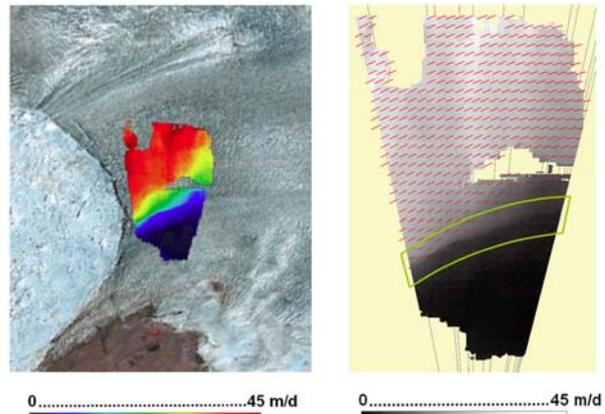

Figure 11: Colour and grey value coded velocity field calculated from the corrected laser scan sequence

The left part of figure 11 shows a colour coded velocity field overlaid on a July 2007 Landsat satellite image of the glacier. An increase of the velocity from the margin to the centre is clearly visible. It can also be seen that the velocity decreases with larger distance to the glacier front. From the corrected data, maximum velocities of 40 m/d could be obtained. This result corresponds well to 2007 tachymeter measurements as well as to 2004 image sequence processing results (Maas et al., 2006 and Dietrich et al., 2007) and to results obtained from tracking in multi-temporal satellite images (Rosenau, 2008).

The right part of figure 11 shows a grey value coded velocity field plus translation vectors. The vectors show a slight turn in the flow direction, which is also visible in satellite images. Furthermore, the border between flowing and dead ice can be seen as a discontinuity in the velocity field (green frame). Hence, some assumptions on the underground of the glacier

could be derived from the results of multi-temporal laser scanner data processing.

All results presented here are intermediate results. Further improvements of the method are necessary to allow for solid interpretations. Basically it can be claimed that velocity differences perpendicular to the scan direction can currently be interpreted more reliably than velocity differences in scan direction due to effects which mainly occur perpendicular to the scan direction.

7. CONCLUSIONS

To the author's knowledge, the publication describes the first application of a long range terrestrial laser scanner to observe a Greenland outlet glacier. Provided that the topography in the vicinity of the glacier tongue allows for suitable instrument stationing, a long range terrestrial laser scanner may be used for multiple purposes:

- Determination of a digital surface model of the glacier: This surface model may be used for the analysis of crevasse patterns. It may also be used to facilitate the georeferencing of monocular image sequence analysis results with the goal of determining glacier surface velocities with high spatial and temporal resolutions. Multi-temporal scans may be used for monitoring local ice mass balance and thinning effects. In our measurements with a Riegl LPM-321 prototype, we achieved a maximum range of 4 km on glacier ice.

- Determination of the height of the glacier front: For Jacobshavn Isbrae, we determined a maximum glacier front height of 135 meter above sea level.

- Determination of 3D glacier surface velocity fields: Multi-temporal laser scanner data acquired at short time intervals allow for the determination of high resolution velocity fields in the region of the glacier tongue. This can be performed by standard image analysis techniques, if the 3D point cloud data are projected into a regular grid. Translation vectors between consecutive datasets can be determined by cross correlation. In our measurements, we determined a maximum glacier movement velocity of 40 meter per day. Some technical problems enforced a careful handling of the data and the development of a correction strategy to take into account timing and angular reference variations.

Compared to terrestrial image sequence analysis for glacier surface velocity field determination (Maas et al, 2006), multi-temporal laser scanner datasets offer some advantages: The data is directly 3D, while monocular image sequence processing requires camera orientation data and distance information for the transformation from image to object space. Moreover, the technique is independent from sunlight and from effects of shadows, which may disturb tracking glacier surface patterns in image sequences. On the other hand, the cost of the instrument and the technical effort is significantly higher. In addition, the beam divergence of 0.8 mrad poses limitations to the spatial resolution, and the scan rate (10 points per second at maximum range) limits the temporal resolution.

Future research will concentrate on the further development of multi-temporal 3D point cloud matching. Techniques such as ICP (iterative closest point – Chen/Medioni, 1991 and Besl/McKay, 1992) or 3D-LSM (Maas, 2002 and Grün/Akca, 2005) will allow not only for the determination of horizontal translation vectors, but also for vertical translations. Moreover,

they can be directly applied to data in a TIN structure, avoiding the necessity of raster interpolation.

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