ANALYSIS OF THE MOTION BEHAVIOUR OF JAKOBSHAVN ISBRÆ GLACIER IN GREENLAND BY MONOCULAR IMAGE SEQUENCE ANALYSIS

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ABSTRACT:

Jakobshavn Isbræ on the west coast of Greenland is one of the fastest and most productive glaciers in the world. It has been moving with an average velocity of 20 meters per day over a long time, producing to total annual iceberg volume of 30 - 40 km^3. In recent years a dramatic retreat of the glacier front has been observed. At the same time, a significant increase of the moving velocity has been reported. In summer 2004, a terrestrial photogrammetric measurement campaign has been conducted at this UNESCO world natural heritage site with the goal of determining precise spatio-temporal velocity fields at the tongue of Jakobshavn Isbræ glacier from high resolution digital camera image sequences.

The characteristics of the glacier movement suggest a primarily one-dimensional motion field, possibly superimposed by tide-induced height changes. The velocity component perpendicular to the general flow direction of the glacier can be considered negligible. Therefore terrestrial monocular image sequences, recorded by a high resolution stillvideo camera, were processed to analyze the motion behavior of the glacier. Trajectories describing the glacier motion were determined by adapted image matching techniques based on the natural surface texture of the glacier. A scale factor for each image space trajectory was derived from a geodetic-photogrammetric network.

From these image sequences, transformed into object space, the daily motion rate of glacier surface structures could be determined at a precision of a few centimeters over a field of view of approximately 2x2 square kilometers. The results obtained from processing image sequences recorded over 12-36 hours show daily motion rates of 40 meter per day and a clear correlation of the height component with the tidal curve. This indicates that the glacier tongue is floating on the fjord. The results of the photogrammetric measurements form a valuable basis for glaciological research on the changing behavior of Jakobshavn Isbræ.

1. INTRODUCTION

Jakobshavn Isbræ (greenl. Sermeq Kujalleq) is one of the most active glaciers in the world. It calves through the Kangia-Fjord and the Disko Bay into Davis Strait at the west coast of Greenland (Figure 1). With a motion rate of 20 meters per day and an annual iceberg production of 30-40 km^3, it drains a substantial 7% of the annual precipitation over the Greenland ice shield (Echelmeyer et al., 1992). First geodetic measurements for the determination of the moving velocity of the glacier tongue have been conducted more than 100 years ago by (Hammer, 1893) and (Engell, 1904). In the 50s and 60s, XY glacier motion velocity profiles of 19 glaciers at Greenland's west coast were determined from 1 : 50'000 aerial images (Carbonell 1968, Bauer 1968). The results of this campaign showed a uniform motion pattern with maximal motion rates of 20-22 meters per day for Jakobshavn Isbræ. The standard deviation of the motion vector, obtained as a difference between aerial images acquired at a five days time base, was in the order of 1% of the motion rate (Carbonell, 1968).

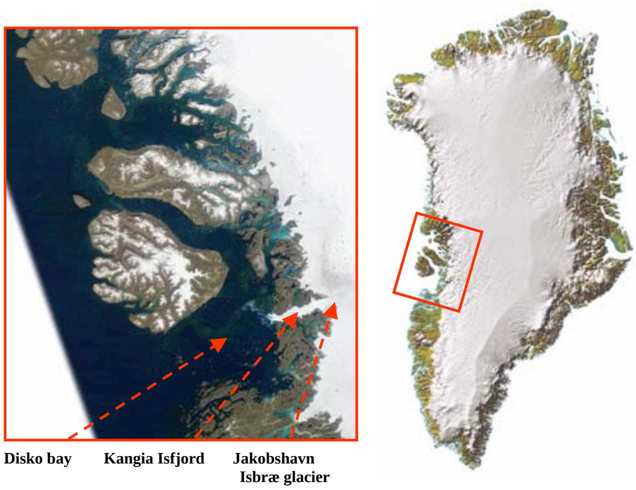

Figure 1: Geographic situation of Jakobshavn Isbræ glacier and Kangia Isfjord

Figure 2: Map of Jakobshavn Isfjord

The glacier tongue of Jakobshavn Isbræ and the Kangia fjord together form Ilulissat Isfjord (Jakobshavn Isfjord, Figure 2), which was declared UNESCO world natural heritage in 2004 (Weidick et al., 2004; Bennike et al., 2004). Until 2000, the glacier was in a quasi-stable condition and calved into Kangia fjord as a 10 km wide ice stream. Since then, a dramatic retreat of the glacier front has been observed, with the glacier now calving into the fjord in two separate ice streams from north and east (Figure 3).

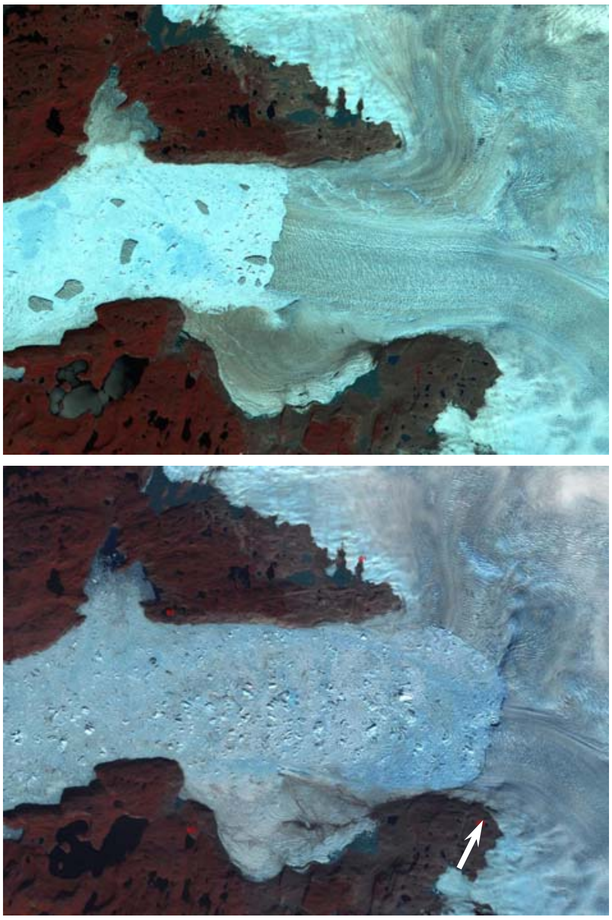

Figure 3: Retreat of the Jakobshavn Isbræ glacier front (Landsat scenes from 7.7.2001 and 8.9.2004)

At a width of the Kangia fjord of about 9-10 km at the eastern end, the retreat of the glacier front over a period of only three years (2001-2004) amounted to more than 10 km. At the same time, airborne laserscanner measurement campaigns showed a thinning of the glacier tongue of more than 10 meters per year (Thomas et al., 2003), and an increase of the motion velocity to 35 meters per day was obtained from satellite images (Joughin et al., 2004).

2. TU DRESDEN 2004 FIELD CAMPAIGN

In August 2004, TU Dresden (Institute of Photogrammetry and Remote Sensing, Institute of Planetary Geodesy) conducted a photogrammetric measurement campaign at the tongue of Jakobshavn Isbræ. The goal of the expedition was the determination of precise spatially and temporally resolved glacier motion fields as a basis for understanding the recent ice mechanics of the glacier. To warrant both a high spatial and temporal resolution, terrestrial image sequences of the glacier tongue were taken with a high resolution camera placed on a hill. The first goal of the campaign was the verification of recent measurements on the increased velocity of the glacier motion. Beyond this, short time motion variations should be determined and analyzed with special emphasis on the height component. These short time height variations can be expected if the glacier tongue is floating on the fjord, which had not been proven so far. The desired combination of high spatial and temporal resolution can only be obtained from terrestrial image sequences. The results of the measurements can also be used for the development of models for a tide-dependent correction of velocity fields obtained from satellite InSAR.

For reasons of local topography and accessibility, the measurements had to be limited to the southern ice stream, which transports the larger ice volume. This ice stream can be observed from a distance of 2-4 km from a hill at the southern edge of the glacier (see arrow in Figure 3). The northern ice stream is currently hardly accessible for terrestrial measurements.

3. PHOTOGRAMMETRIC DATA ACQUISITION

During the 14 day field campaign, several image sequences were recorded in the area of the glacier front using a 4500x3000 pixel digital stillvideo camera Kodak DCS 14n (Figure 4). The intervallometer mode of the camera allows for taking image sequences at pre-defined time intervals over a long period of time. With a power consumption of 6 Watt in standby mode, an external power supply is required. During the field campaign, a 24 AH battery was used, providing power for about 48 hours.

Figure 4: Kodak DCS 14n at Jakobshavn Isbræ

Figure 5: Jakobshavn Isbræ measurement image

The image sequences taken during the campaign covered time periods of 12-36 hours. Longer sequences could not be taken due to changing weather conditions and the lack of a weather-proof camera housing. To prove the presumed tide induced motion variations, image sequences should cover a minimum of 24 hours. At 70° northern latitude, illumination conditions allow for this from mid April to mid August. The intervallometer of the camera was set to 30 minutes. Camera orientation variations caused by wind effects, warming up of the tripod legs and instabilities of the ground were compensated by stable reference targets in the foreground of the images (Figure 5). These orientation variations caused image coordinate effects of up to 10 pixels.

Only monocular image sequences were taken. Stereoscopic imaging with a sufficient base-to-height ratio turned out to be impossible as a consequence of the local topography. Moreover, the extremely rugged glacier surface (Figure 6) caused a strong decorrelation of stereoscopic images, making stereo matching rather unreliable. This can be accepted, as the dynamic of glacier movement suggests no significant across-track motion of the glacier, so that XZ-components of velocity information delivered by a monoscopic camera oriented perpendicular to the glacier moving direction will be sufficient.

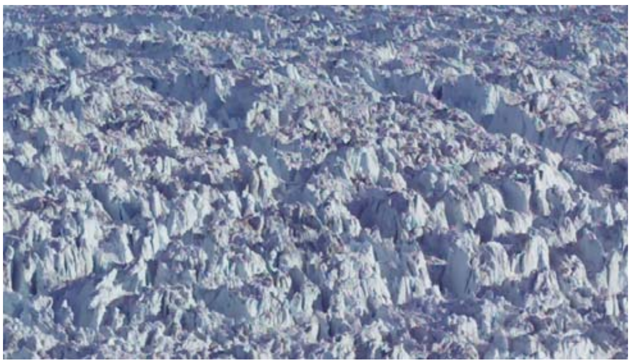

Figure 6: Section of Figure 5

Motion information determined in monoscopic image sequences requires image scale information in order to be translated into object space. For this purpose, a combined geodetic-photogrammetric network was measured, allowing for a rough rectification of the images and the definition of an individual scale factor for each image space motion trajectory (Maas et al., 2005).

4. DATA PROCESSING

Figure 5 shows a single image from a 26 hours image sequence, recorded on 20 August 2004 using a 50 mm lens. Cross correlation and least squares matching were used to track patches at pre-defined positions or at a regular pattern through the image sequence. The extremely rugged glacier surface, combined with cloud effects and shadows moving over almost 360°, caused a strong decorrelation of subsequent images in the image sequence and turned out to be rather problematic in applying matching techniques. Modelling these effects would require a high quality surface model of the glacier, which seems almost an impossible task to solve. Instead, the effects introduced by the decorrelation were largely compensated by choosing large patches of 40x40 pixels and by continuity constraints in the area based matching techniques. The trajectories obtained from matching were corrected by camera orientation change effects obtained from the reference targets in the image foreground. Finally, non-linear filtering was applied to the results, eliminating non-plausible discontinuities in the trajectories. These measures allowed for matching between subsequent images at reasonable reliability with a standard deviation of shift parameters in the order of 0.1 pixel. A matching process relating each image to the first image of the sequence, desirable from an error propagation point of view, failed in many cases. Optionally, drift effects caused by error propagation in subsequent image matching can often be compensated by an additional matching between two images 24 hours apart.

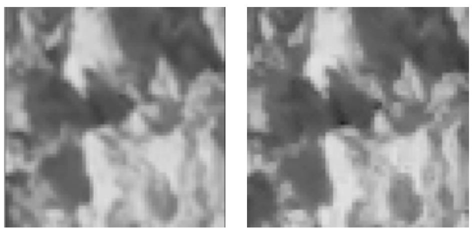

Figure 7: 40x40 pixel patch in two subsequent images

Similar problems were also reported for interactive processing of multi-temporal aerial images taken at a time base of 4-5 days (Carbonell, 1968).

5. RESULTS

1500 image points, arranged on a regular grid in image space, were tracked through the whole image sequence consisting of 52 frames. The transformation of the image space trajectories into object space was performed on the basis of a geodetic-photogrammetric network, providing scale information for each trajectory start point. This step required some user interaction due to the difficulty of reliable stereo image matching.

Despite some problems occurring in image matching as mentioned in section 4, the results of glacier pattern image tracking clearly show the expected glaciological phenomena. The trajectories derived from the image sequences show a rather uniform motion of the glacier in its flow direction. Patches in the image foreground move about 130 pixels per day, translating into a daily glacier motion of 40 meters. This value means a doubling of the glacier velocity for august 2004 as compared to earlier measurements less than 10 years ago. These results are also confirmed by results obtained from satellite InSAR data processing by NASA, who obtained motion rates of 35 meters per day for 2003 (Joughin et al., 2004). Similar effects are also reported for glaciers on Greenland's east coast (de Lange et al., 2005).

The analysis of the vertical component of the trajectories shows a very significant variability. Figure 8 shows the height component of a glacier point trajectory over 24 hours, showing a sinusoidal behavior with two clear peaks. These peaks correlate very well with the tidal curve for the Ilulissat tide gauge. The vertical range of the height component, corrected by camera motion effects and the linear glacier movement, amounts to 5 pixels or about 1.50 meters. Compared to the gauge curve, we see a slight damping and a latency, which can be explained by effects of ice mechanics.

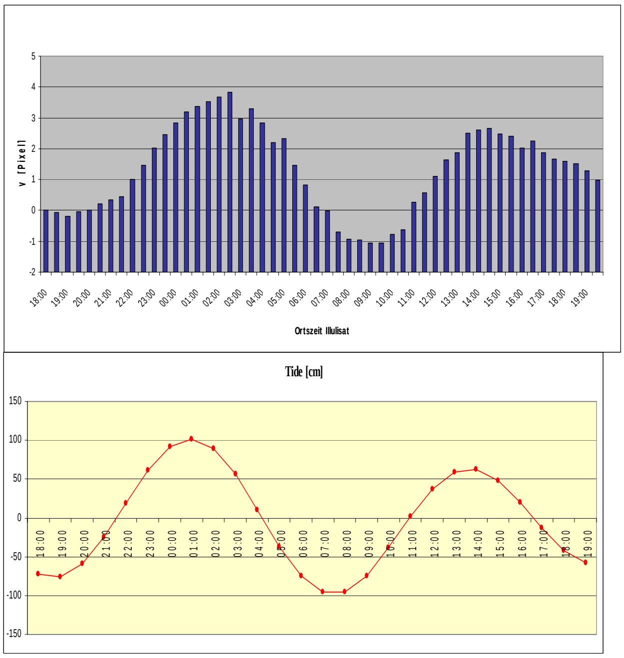

Figure 8: Vertical motion component of a point close to the glacier front over 24 hours, tidal curve for Ilulissat

Other points close to the glacier front confirm this behavior (figure 9), while the vertical motion range decreases upstream. These effects form a clear indication for the glacier tongue floating on the fjord, disproving an earlier hypothesis by (Bauer, 1968) stating that the glacier were not floating on the fjord.

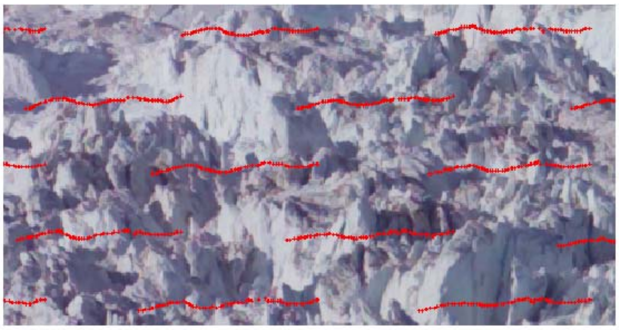

Figure 9: 2D trajectories for a section of figure 5

A movie showing the glacier motion can be downloaded from http://www.tu-dresden.de/ipf/photo/forschung/gletscher.htm

6. OUTLOOK

Terrestrial high resolution digital image sequence processing can deliver a valuable contribution to glaciological research at fast Arctic or Antarctic glaciers. The method offers the advantages of a very high temporal and spatial resolution, combined with flexible and cost-effective data acquisition. Obvious disadvantages are the limited area coverage and long term observation capabilities as well as the topography dependency. In this sense, terrestrial photogrammetry may provide a complementary supplement to airborne or satellite data acquisition.

Automatic image sequence processing turned out to be challenging due to effects caused by the extreme glacier surface topography, but careful handling of area based matching tools could provide good results. Besides the escalation of the glacier motion velocity from earlier 20 meters per day to now 40 meters per day, the results clearly show a tide-induced height variation of the glacier tongue motion.

Future photogrammetric measurement campaigns could benefit from a number of improvements: Weather-proof camera housing will allow for longer observation periods. A further improvement of the data processing chain can be achieved by the integration of robust estimation techniques into the pattern tracking procedures. Finally, multi-temporal terrestrial laserscanner data acquisition may depict an interesting alternative for well accessible glaciers at shorter observation distances. Laserscanners are independent on image texture or texture changes caused by shadowing, and they deliver 3D coordinates, allowing for the analysis of all three components of the motion field.

7. ACKNOWLEGMENTS

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