DETERMINATION OF SPATIO-TEMPORAL VELOCITY FIELDS ON GLACIERS IN WEST-GREENLAND BY TERRESTRIAL IMAGE SEQUENCE ANALYSIS

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ABSTRACT:

Some glaciers in Greenland are currently showing dramatic changes: A fast retreat of the glacier front, thinning and acceleration of glacier movement. As a prominent example, Jacobshavn Isbræ glacier has accelerated from 20 meters per day to 40 meters per day within a few years. These effects can very well be observed by photogrammetric and remote sensing techniques. In the paper, we report on recent measurements at three glaciers in West Greenland: Jacobshavn Isbræ, Eqip Sermia and Støre Qarajaq. The paper will concentrate on the determination of spatio-temporal velocity fields from high resolution terrestrial image sequences captured by a 39-Megapixel camera. In addition, the glacier front retreat has been mapped from multi-temporal satellite images, and a terrestrial laserscanner has been used to determine glacier surface models and glacier motion from multiple scans. The results of the photogrammetric measurements form a valuable basis for glaciological research on the changing behavior of glaciers.

1. INTRODUCTION

Greenland has an area of 2,166,086 km², which is ~81% covered with ice. The function of draining the precipitation on the ice cap is largely taken by a number of large outlet glaciers. The most prominent of these glaciers is Jacobshavn Isbræ (Sermeq Kujalleq) at the West cost of Greenland (Figure 1). Jacobshavn Isbræ is one of the fastest and most productive glaciers in the world. Its velocity, first determined in the late 19^{th} century (Hammer, 1893), has been more or less constantly at about 20 meter per day for a long time. The glacier has a catchment area of about 110‘000 km^2 and drains ca. 7% of the total precipitation of Greenland (Echelmeyer et al., 1992). Its annual iceberg production has been estimated to be in the order of 30 km^3 until 2000. It is responsible for 0.06 mm/a or 4% of the annual see level rise (Joughin et al., 2004). Jacobshavn Isbræ and the Kangia Fjord have been declared UNESCO world natural heritage site in 2004 (Bennicke et al., 2004).

In the past few years, the motion behavior of Jacobshavn Isbræ has changed dramatically: The glacier front has retreated by more than 12 km, and the velocity has increased by about a factor two. In the following, the retreat of the glacier front will be documented by satellite images (section 2), and the spatio-temporal motion behavior will be analyzed by terrestrial image sequences (section 3) and multi-temporal terrestrial laserscanner data (section 4).

Furthermore, the changes of two other glaciers in West Greenland, Støre Qarajaq and Eqip Sermia (Figure 1), are described in section 5 and 6.

For these studies, we used Landsat image data from 2001, 2004 and 2007, aerial image data from 1957/58 (Bauer 1968, Carbonell/Bauer 1968) as well as field data from expeditions to Jacobshavn Isbræ in 2004 (Maas et al., 2006; Dietrich et al., 2007) and to Jacobshavn Isbræ, Eqip Sermia and Støre Qarajaq in 2007.

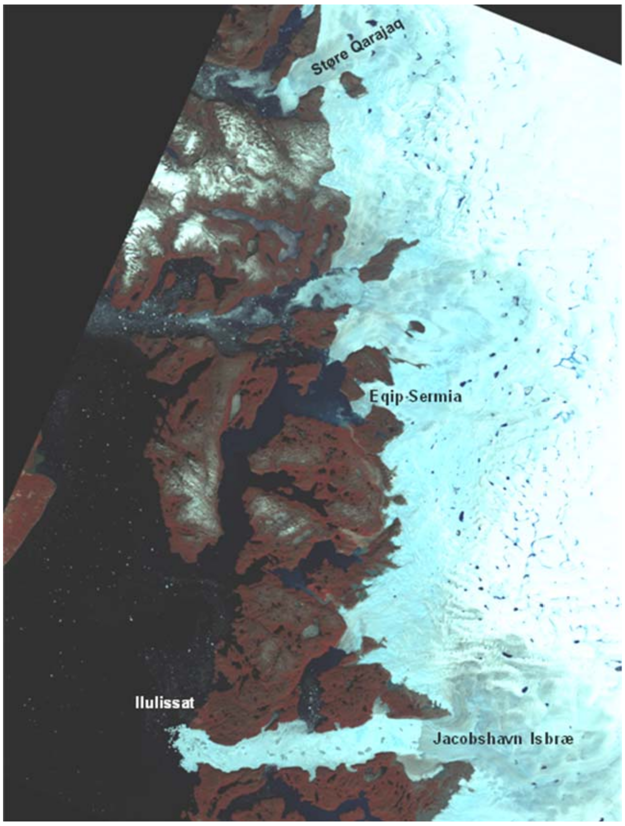

Figure 1. West Greenland with Støre Qarajaq, Eqip Sermia and Jacobshavn Isbræ glaciers (Landsat 2001 false color image)

2. JACOBSHAVN ISBRÆ GLACIER FRONT RETREAT

Jacobshavn Isbræ (69°10’N, 49°40’W) and some other glaciers in Greenland have recently been showing dramatic changes. Figure 2 shows Landsat images from 2001, 2004 and 2007. The glacier front of Jacobshavn Isbræ has retreated by about 12 km between 2001 and 2004, 11 km thereof in spring 2003 (Podlech and Weidick, 2004). A further retreat of 1-2 km can be observed between 2004 and 2007.

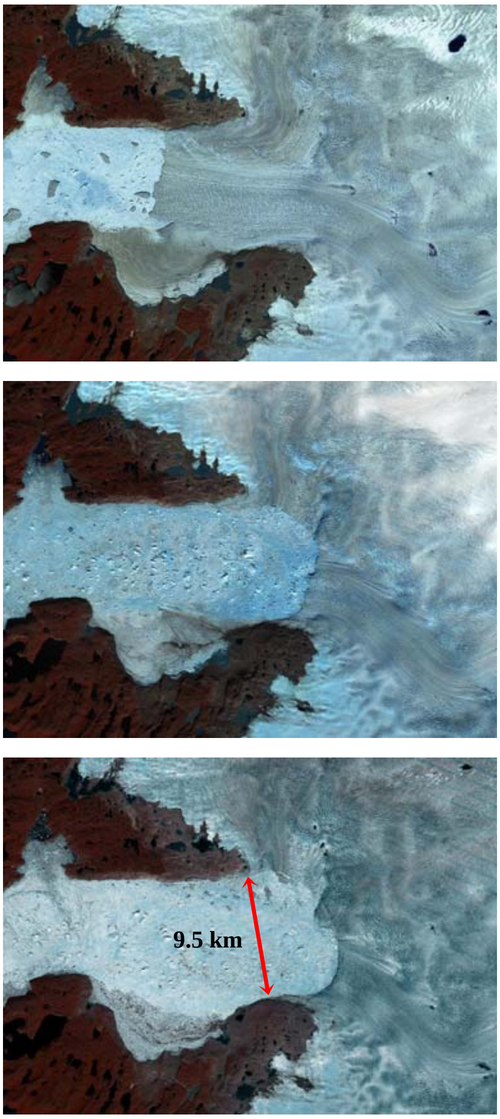

Figure 2. False color Landsat images of Jacobshavn Isbræ (7.7.2001, 8.9.2004, 8.7.2007)

Weidick et al. (2004) present glacier front positions dating back to 1850, showing a retreat by 26 km between 1850 and 1950, followed by a period of stability until 2002. Georgi (1958) reports on a fast advance of the front by 25 km between 1750 and 1870, mainly based on historic oral testimony. Short term variations of the glacier front position by several hundred meters may occur within days or weeks, and seasonal changes are in the order of 2-4 kilometres (Podlech and Weidick, 2004). With respect to the 1850 front position of (Weidick et al., 2004), we get a total front retreat of 41 km, with about 33% thereof happening in the past six years. These changes coincide with a decade of sustained Arctic warming (Christoffersen and Hambrey, 2006). On the other hand, Georgi (1958) developed a hypothesis on an ice blockage in the Kangia fjord, which had lead to the 1750-1870 advance, and predicted a further retreat of the glacier as a long-term consequence of a collapse of the ice blockage.

The fast retreat of the glacier front has been accompanied by a significant thinning of the glacier tongue and an acceleration of the glacier movement: Thomas et al. (2003) derived a thinning of the glacier tongue of more than 10 meters per year from airborne laserscanner measurements since 1997, after a short period of thickening 1991-1997. Joughin et al. (2004) reported an increase of the motion velocity obtained from satellite images from a former 20 meters per day to 35 meters per day. The ice discharge, deduced from radio echo sounding and seismic data, grew from 24 km^3/a to 46 km^3/a between 1996 and 2005 (Rignot and Kanagaratnam, 2006). As a consequence of these developments, the calving behaviour of the glacier has also changed drastically: While the glacier used to produce majestic icebergs, some more than 1km^2 large, it is now producing much smaller fractions of icebergs.

3. DETERMINATION OF SPATIO-TEMPORAL VELOCITY FIELDS AT JACOBSHAVN ISBRÆ

Jacobshavn Isbræ is also referred to as an ice stream, which is defined as a fast current of ice embedded in an ice sheet. The pattern of the ice stream can also be recognized in Figure 3. With the retreat of the glacier front, the ice stream was split into a main part coming from east and a smaller part coming from north after 2001. Early geodetic measurements of the motion velocity of Jacobshavn Isbræ date back more than 100 years ago. Hammer (1893) and Engell (1904) determined a moving velocity of about 20 meters per day, making Jacobshavn Isbræ one of the fastest glaciers in the world. This value was confirmed by Carbonell and Bauer (1968), who determined XY velocity vector profiles on 19 West Greenland glaciers from repeated small scale aerial imagery and showed 20-22 meter per day for Jacobshavn Isbræ. Prescott et al. (2003) also confirmed 20 meter per day on the basis of 1985 aerial images. While Echelmeyer and Harrison (1990) found no significant seasonal variations in the glacier velocity obtained from terrestrial geodetic measurements 1984-1986, Luckman and Murray (2005) reported a 10% velocity increase between May and July 1995 on the bases of correlation-based feature tracking in 35-day repeat-pass satellite SAR images. Joughin et al. (2004) used aerial images, interferometric synthetic aperture radar (InSAR), Landsat-images and airborne laserscanner data to determine the velocity between 1985 and 2003. They report a sudden increase of the velocity after 1997, reaching 26 meter per day in 2000 and 35 meters per day in 2003.

Figure 3. Jacobshavn Isbræ and Kangia Fjord, 2004+2007 observation points (arrows)

The movement of outlet glaciers can be characterized by a primarily one-dimensional motion field, which may be superimposed by tide-induced height changes, if the glacier tongue is floating on the fjord. Long-term velocity changes may be determined from satellite imagery. Considering the rapid movement and surface change of the glaciers, the potential of feature tracking in optical satellite imagery is limited by the image resolution, the repeat interval and the durability of features, which are usually crevasse patterns. Repeat-pass InSAR has a high precision potential, but is not applicable to a fast-moving glacier at 35-day revisit cycles due to an almost complete de-correlation caused by changes in the extremely rugged glacier surface (Figure 4) and changing crevasse patterns; it is also prone to aliasing in regions with high strain rates (Abdalati and Krabill, 1999). Oblique high resolution optical imagery would require a digital surface model, which is not available as a consequence of the ever changing crevasse patterns. Aerial imagery offers a better resolution and a higher flexibility in choosing suitable time intervals, but is rather costly. Short-term effects – especially tide-induced effects – can very well be determined at high both spatial and temporal resolution by terrestrial photogrammetric techniques using a camera observing the glacier from a hill, provided that the topography around the glacier allows for it. As the velocity component perpendicular to the general flow direction of the glacier can be considered negligible, monocular image sequences, recorded by a high resolution camera, can be used to analyze the motion behaviour of the glacier. During the midnight sun period, 24+ hour sequences can be acquired at almost arbitrarily short time intervals.

Figure 4. Image of Jacobshavn Isbræ glacier front area (Maas et al., 2004), observation point marked in Figure 3

In our 2004 measurement campaign, we used a 14 Megapixel Kodak DCS14n camera. In the 2007 campaign, a 39 Megapixel camera IGI DigiCAM was available (Figure 5). The cameras were operated in an intervallometer mode, taking images at regular time intervals (typically 10 or 15 minutes) over time periods of 24-72 hours.

Figure 5. IGI DigiCAM 39 MPix camera

Trajectories describing the glacier motion were determined by adapted area based image sequence tracking techniques based on the natural surface texture of the glacier (Maas et al., 2006). A scale factor for the object space transformation of each image space trajectory was derived from a geodetic-photogrammetric network (Maas et al., 2006) and a laserscanner glacier surface model (section 4). From these image sequences, transformed into object space, the daily motion rate of glacier surface structures can be determined at a precision of a few centimeters for points at a distance of from 2-5 km from the camera. Camera orientation variations in the order of several pixels, which were caused by wind effects, warming up of the tripod legs or instabilities of the ground, were compensated by stable reference targets in the foreground of the images, which can be seen in Figure 4 (Maas et al., 2006).

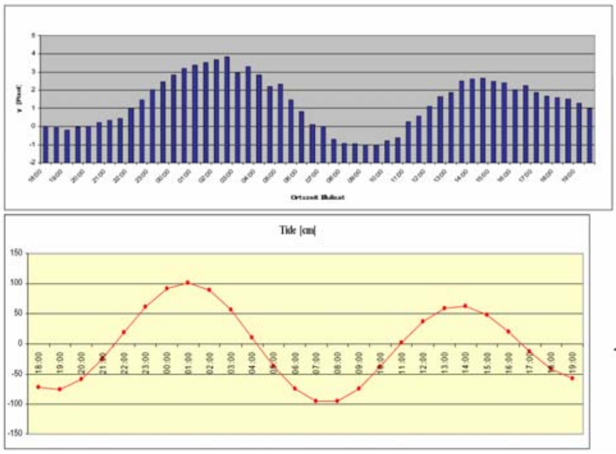

Figure 6. Trajectory from image sequence tracking (top), tidal curve (bottom)

Figure 6 shows the result of image sequence feature tracking for one point (out of 4500) over 24 hours in an image sequence of August 20th, 2004. The trajectory has a length of 140 pixels, which corresponds to 40 meters. This value is also confirmed by (Rosenau, 2008) on the basis of area based tracking between two consecutive ASTER images from 2004. It documents an ongoing acceleration of the glacier movement with respect to the 2003 measurements presented by Joughin et al. (2004), and a doubling of the motion velocity within about 5 years. Similar effects are also reported for glaciers on Greenland's east coast (de Lange et al., 2005). In addition to the horizontal movement in flow direction, a vertical signal can clearly be recognized. It amounts to about 5 pixels or 1.50 meters and correlates very well with the tidal curve for the Kangia Fjord. This proves – in contrast to conclusions by Bauer (1968) – that the glacier tongue is floating on the fjord. With respect to the tidal curve, the glacier point trajectory shows a slight latency of about 40 minutes and a damping of the amplitude (1.50 meter for the trajectory, 1.95 meter for the tidal curve. This effect can be explained by effects of ice mechanics.

A total of 4500 glacier point trajectories were tracked. In a next step, all trajectories were compared to the tidal curve. This was performed by treating the tidal curve as a master trajectory and fitting it into the individual measured trajectories in a least-squares adjustment approach (Dietrich et al., 2007). The transformation included a translation to the trajectory origin, a length scale to adapt to variations of the velocity in different parts of the glacier, a vertical damping factor and a surface vector tilt to adapt to the local steepness of the glacier (Figure 7). Outliers were removed applying a 3σ-rule.

The trajectory matching process was performed for all 4500 tracked glacier points (Dietrich et al., 2007). 2% of the trajectories had to be removed as outliers. The result allows for a graphical display of the local velocity, the participation with the tidal movement (Figure 8) and the downhill motion gradient, plus the RMS for each parameter.

Points close to the glacier front show 90-100% participation with the tidal movement. Points which are about 700 pixels away from the front show almost no participation. This allows for the localization of the grounding line of the glacier, which is the line where the glacier touches the ground of the fjord. Beyond the grounding line, the glacier is floating on the fjord. As one can see from Figure 8, the glacier had almost reached its grounding line in August 2004. With a further retreat of the glacier front after 2004 (cmp. Figure 2), there should be no more floating tongue anymore.

This was confirmed during the 2007 expedition: A glacier will only produce huge icebergs, if its tongue is floating. A glacier, which has reached its grounding line, will produce more and smaller icebergs. In 2007, only few large icebergs were present in the rear part of the fjord. This can also be seen in the Landsat images shown in Figure 2.

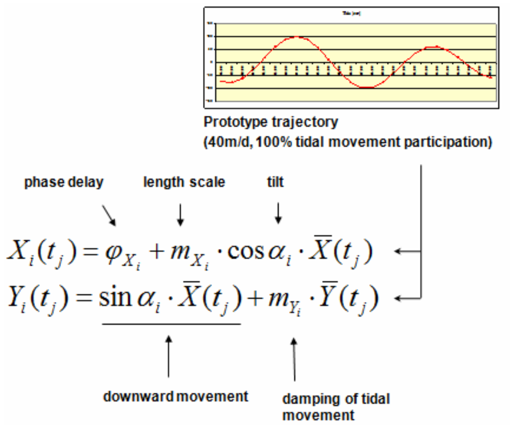

Figure 7. Trajectory matching approach

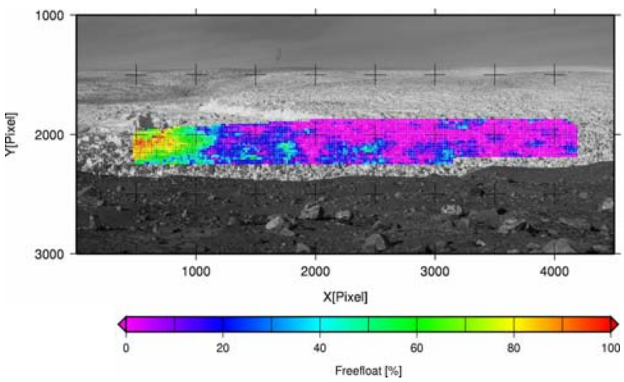

Figure 8. Tidal movement of the glacier in percent of free float

4. TERRESTRIAL LASERSCANNING AT JACOBSHAVN ISBRÆ

In addition to terrestrial image sequences, a long range terrestrial laserscanner with a maximum range of 4 km on glacier ice has been used in the 2007 campaign at Jacobshavn Isbræ. The laserscanner measurements were used for three purposes:

- Monitoring of glacier thinning.
- Determination of the glacier front height.
- Determination of a digital glacier surface model as a basis for terrestrial image sequence geo-referencing.
- Determination of spatio-temporal velocity fields from feature tracking in multi-temporal scans.

The dimension of the glacier and the topography next to the glacier posed severe requirements to the selection of a proper instrument, as a maximum range of several kilometres is necessary to scan the main part of the ice stream, which is at a distance between 1.5 - 4.0 km from the observation point. The only commercial terrestrial laserscanner instrument to fulfil this requirement is the Riegl LPM-321 (Figure 9). In practical tests at Jacobshavn Isbræ, a maximum range of 4 km could be proven. The downside of the excellent range capability if a measurement rate of only 10 points per second at maximum range settings, taking 8 hours for a 250’000 points surface scan. See (Schwalbe et al., 2008) for a more detailed description of the scanner and its potential in glaciology.

Figure 9. Riegl LPM-321 at Jacobshavn Isbræ

Figure 10 shows a triangulated surface model of the front part of Jacobshavn Isbræ, obtained from Riegl LPM-321 terrestrial laserscanner data. The glacier front height obtained from the data is 135 meters. The surface model can also be used in the georeferencing of the image sequence data (section 3): A local scale factor for each image point can be determined by the intersection of the image ray with the surface model.

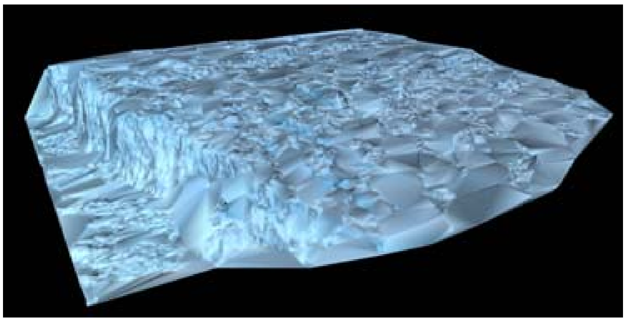

Figure 10. Terrestrial laserscanner glacier front surface model of Jacobshavn Isbræ, July 2007

Schwalbe et al. (2008) describe the determination of spatio-temporal velocity fields from automatic feature tracking in multi-temporal glacier surface scans. Similarly, Abdalati and Krabill (1999) determined velocities on Jacobshavn Isbræ by tracking crevasses in multi-temporal airborne laserscanner data. Compared to the image sequence processing approach as outlined in section 3, the laserscanner data sequence processing approach has the advantages of independence on sunlight and surface texture. While image sequence processing will only deliver 24-hour trajectories during the polar summer, laserscanning can basically be applied at arbitrary times. Moreover, laserscanner data processing will not suffer from effects caused by moving shadows as a consequence of the rugged glacier surface and the 360° path of the sun (Maas et al., 2006). Disadvantages are the cost of the instrument, the electrical power requirements and the limited resolution caused by the beam divergence of 0.8 mrad and the slow scan rate.

5. OBSERVATIONS AT STØRE QARAJAQ

Støre Qarajaq at (70°23'N, 50°34'W) was the 2nd fastest glacier in West Greenland in the late 50s according to the measurements of Carbonell and Bauer (1968). It was measured with a speed of up to 17.5 meter per day close to the 5 km wide glacier front (Figure 11). In contrast to Jacobshavn Isbræ, its front position is stationary with respect to 50 years ago, as can be derived from a comparison of 2001, 2004 and 2007 satellite images with aerial images from the late 50s published in (Carbonell and Bauer, 1968). Image sequences for glacier motion analysis were taken from a mountain on the north-western shore of the glacier. The processing state of the 2007 image sequence data does not allow for a final description of the motion behavior yet, but a doubling of the glacier velocity (as for Jacobshavn Isbræ) could not be observed.

6. OBSERVATIONS AT EQIP SERMIA

Eqip Sermia (Figure 12) at (69°47'N, 50°15'W) also shows a front position, which is almost the same as 50 years ago. The glacier motion speed close to the 4 km wide glacier front was measured with a relatively low 3.6 meter per day in the late 50s (Carbonell and Bauer, 1968). Here, Rignot and Kanagaratnam (2006) report a 30% velocity increase between 2000 and 2005. Rosenau (2008) determined velocities between 2.5 and 5 m/d on the basis of area based tracking between two consecutive ASTER images from 2006. For the nearby Sermeq Avannarleq, Rignot and Kanagaratnam (2006) report a 11% velocity decrease between 2000 and 2005.

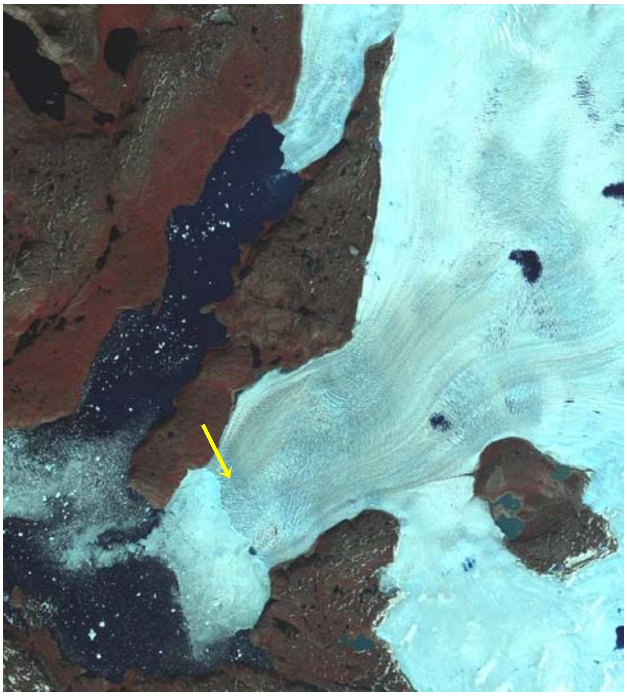

Figure 11. Støre Qarajaq (2001 Landsat false color image), 2007 observation point

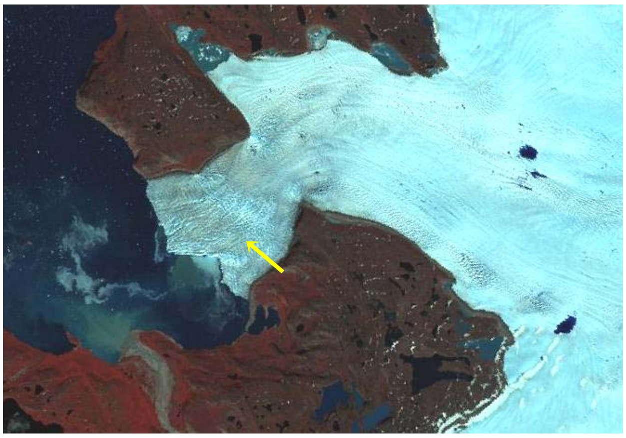

Figure 12. Equip Sermia (2001 Landsat false color image), 2007 observation point

7. CONCLUSION

Some glaciers in Greenland – with the Jakobshavn Isbræ as the most prominent example – are currently showing a dramatic retreat of the glacier front and a rapid acceleration of the glacier motion speed.

Recent glacier front retreat can very well be observed from optical satellite imagery. Aerial imagery allows to trace back glacier fronts to the 1930s, while geodetic mapping and oral testimony gives information on Jakobshavn Isbræ front positions dating back to the mid of the 18th century. Jakobshavn Isbræ has been almost stationary between 1950 and 2000. Starting in 2003, it showed a sudden retreat, which was still continuing at reduced pace in summer 2007 and accumulates to more than 12 km. This retreat coincides with a period of significant warming in Greenland. In contrast, however, Støre Qarajaq and Eqip Sermia, which are only 200 km and 100 km north of Jakobshavn Isbræ, show a glacier front position, which is almost stationary in comparison to the 1950s situation.

The processing of image sequences of a high resolution terrestrial camera observing the glacier front region delivers glacier surface velocity fields at very high spatial and temporal resolution, which form a valuable basis for glaciological research on the changing behavior of glaciers. 2004 terrestrial photogrammetry data at Jakobshavn Isbræ showed an increase of the glacier moving velocity from 20 meter per day in the 20th century to 40 meter per day. A detailed analysis of the glacier surface motion trajectory patterns allows for the detection and measurement of tidal effects in the glacier motion. On the basis of the data, it could be proven that the tongue of Jakobshavn Isbræ was floating on the Kangia fjord in 2004. Moreover, the grounding line of the glacier can be derived from the motion data. The 2007 observations show a stagnation of the velocity at this high level and indicate, that the glacier has meanwhile reached its grounding line – with severe consequences for the calving behavior and the origination of large icebergs.

The acceleration of Jakobshavn Isbræ is likely to be related to the rapid glacier front retreat. A similar acceleration effect could not be observed at Støre Qarajaq and Eqip Sermia, which show a stationary glacier front position.

As an alternative or a complement to a camera, a long range terrestrial laserscanner with a maximum range of 4 km on ice may depict an interesting tool for glaciology research. Besides the determination of glacier surface models and glacier front heights, it can also be used to determine glacier surface models and glacier motion from multi-temporal scans.

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