SURFACE VELOCITIES OF A GREENLAND OUTLET GLACIER FROM HIGH-RESOLUTION VISIBLE SATELLITE IMAGERY[1]

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Abstract: A multidisciplinary team of researchers reports the results of a study of the feasibility of utilizing high-resolution Declassified Intelligence Satellite Photographs (DISP) to derive surface speeds of fast-moving Greenland outlet glaciers from tracking surface features on sequential DISP images. The images provide coverage of the entire Greenland Ice Sheet for most of the 1960s and their value as a resource for establishing a baseline for assessing ongoing and future changes in the ice sheet is demonstrated.

INTRODUCTION

One of the major issues in Earth science is to determine and understand the mass balance of the large polar ice sheets. In particular, there is a need to explain the ~10 to 25 cm sea-level rise during the last century (IPCC, 1996). Changes in ice volume contribute directly to global sea level and it may be expected that this contribution will change as a result of the predicted greenhouse warming, although it is not clear by how much or in what sense. Moreover, increased iceberg discharge from the polar ice sheets could trigger a major reorganization in the oceanic thermohaline circulation and consequent large atmospheric changes (Broecker, 1997). There are indications that both the Greenland and Antarctic ice sheets are undergoing changes but there are, at present, too few observations available to allow meaningful quantitative estimates of their current net mass balance. For detecting changes in the polar ice sheets, it is imperative to establish as early a baseline as possible against which future measurements can be compared. In most instances, changes in the polar ice sheets occur gradually and time intervals of several decades may be needed to establish with confidence any trends that may be taking place. The recently declassified reconnaissance satellite photographs from the 1960s (Wheelon, 1997) represent the earliest complete sets of images covering nearly the entire Greenland Ice Sheet. The images were acquired by systems known under the codenames of CORONA, ARGON, and LANYARD. The ARGON system carried a frame camera to take images with a ground coverage of 540 km by 540 km at a resolution of 120 m. The CORONA and the LANYARD systems employed diffraction-limited panoramic cameras and high-

[1]This pilot study was supported by NASA Goddard Project NAS5-30946. We thank Ken Jezek for comments and discussion of an earlier version. Byrd Polar Research Center contribution C-1137.

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Polar Geography, 1999, **23**, No. 1, pp. 71-82.

definition films, rendering images of the Earth's surface with a resolution unsurpassed by any subsequent satellite visible imaging system. The highest-resolution CORONA systems were the KH-4A and KH-4B systems, which have ground resolutions of 2.7 m and 1.8 m, respectively. To provide stereo coverage, CORONA satellites were equipped with two cameras mounted forward and aft at a 30° convergence angle. All systems employed high-resolution film. The KH-4A and KH-4B systems provided images at sufficiently high resolution and quality to determine glacier speeds, identify flow features, and map ice-sheet margins.

PRIOR APPLICATIONS OF DISP

Several studies have demonstrated the feasibility of using Declassified Intelligence Satellite Photographs (DISP) for glaciological applications. Bindschadler and Vornberger (1998) compared 1963 images with a ground spatial resolution of ~150 m with two images from the Advanced Very High Resolution Radiometer (AVHRR) collected in 1980 and 1992 (spatial resolution: 1100 m) and with a series of panchromatic Satellite Pour l'Observation de la Terre (SPOT) images obtained between January 1989 and February 1992 (ground resolution: 10 m). The authors examined the region where ice stream B enters the Ross Ice Shelf and Crary Ice Rise farther downstream. By comparing the relative position of a feature known as ice raft A on the DISP and SPOT images, Bindschadler and Vornberger (1998) estimated an average advection speed of 770 ± 20 m/yr for the period 1963 to 1989. This velocity is considerably greater than the speed measured in the 1980s during ground surveys using satellite receivers (471 m/yr), suggesting that the ice in the region may have slowed in recent years. Jezek (1998) compared DISP images with the high-resolution images collected in 1997 by the Canadian Radarsat-1 to examine changes in flow regimes in the vicinity of Crary Ice Rise. By evaluating the displacement of pronounced surface features over the 35-year interval between the images, Jezek (1998) estimated a speed of ~350 m/yr at 10 km downstream of the northern tip of the ice rise. Sohn et al. (1998) used a sequence of airborne and spaceborne data, starting with a 1962 DISP image, to study changes in the position of the ice margin near Jakobshavn Glacier, west Greenland, as well as seasonal variations in the position of the calving front of this tidal outlet glacier.

All these studies used ARGON images that have a relatively coarse ground resolution of ~150 m. This, in turn, causes considerable errors in the image-to-image co-registration. Bindschadler and Vornberger (1998) quoted an accuracy of ~500 m for the DISP-to-SPOT co-registration, in part attributed to a lack of stationary control points. Because of the long time interval between acquisition of both images (1963–1989), the error in derived speed is acceptably small. However, to establish a 1960s benchline for speeds and to derive time series of velocity, much greater ground accuracy is needed because displacements over intervals of one year or less are considered. For example, a 500 m error in position would lead to an uncertainty in speed of ~700 m/yr if calculated from images one year apart. To obtain a similar uncertainty in speed as given by Bindschadler and Vornberger (1998), an accuracy in image co-registration of ~15 m is required if successive images are one year apart.

The studies of Bindschadler and Vornberger (1998) and Jezek (1998) demonstrate that DISP images can be used to derive glacier speed where pronounced surface features such as ice rise A or distinct patterns of surface crevasses can be identified on subsequent images. Compared to fast-moving outlet glaciers, the surface of the Ross Ice Shelf is comparatively smooth and homogenous and particular surface features are readily identified and persist over many years. The surface of Greenland tidal outlet glaciers, on the other hand, is heavily crevassed with few outstanding features. Moreover, many of these glaciers move at speeds of several km per year and most features cannot be traced over extended periods of time. To successfully derive speeds on these glaciers, individual crevasses need to be tracked from epoch to epoch. The high radiometric and geometric resolution of the CORONA images suggests the possibility for measurements of velocities on fast outlet glaciers in Greenland, where large snow accumulation and surface melting may restrict the use of radar interferometry.

VELOCITY DETERMINATION ON GLACIERS

Several methods have been used to measure the speed at which glaciers move. Early techniques involved placing markers on the surface and measuring their movement relative to a stationary point on surrounding rock (e.g., Forbes, 1859). Satellite positioning systems opened the possibility for repeated positioning of markers on the polar ice sheets where no stationary points are nearby (e.g., Whillans et al., 1987). These methods provide the most accurate displacements but are time consuming and costly because of the field work involved.

Greater spatial coverage and a higher density of velocity determinations can be obtained using repeated aerial photography or visible imagery such as SPOT or LANDSAT. This technique relies on visible features on the glacier surface that can be traced from epoch to epoch, and has been successfully used on Greenland outlet glaciers (e.g., Carbonnell and Bauer, 1968; Dwyer, 1995) and ice streams in West Antarctica (Whillans et al., 1993; Whillans and Tseng, 1995).

Radar interferometry has been applied to measure velocities over the northern part of the Greenland Ice Sheet (e.g., Rignot, 1996; Rignot et al., 1997) by using the phase information from synthetic aperture radar (SAR) images to determine the surface velocity component in the satellite viewing direction (Goldstein et al., 1993; Joughin, Kwok et al., 1996a; Joughin et al., 1998). The actual surface component is estimated by assuming the velocity to be collinear with visible flow features or to be parallel to the surface elevation gradient. The method typically uses images acquired only a few days apart, so that the images are highly correlated. Over longer time periods surface processes such as melting and the scouring or accumulation of snow greatly reduce the correlation and interferometry cannot be applied.

Velocities determined over time intervals of a few days may not be representative of the longer-term averaged speed that is more relevant for assessing the ice-sheet mass balance. For example, Joughin, Tulaczyk et al. (1996) reported on a mini-surge on Ryder Glacier, north Greenland, during which the speed increased roughly threefold over a seven-week period. These authors suggested that the rapid motion, which occurred near the end of the 1995 ablation season, may have been caused by drainage of supra-glacial lakes. Similarly, Reeh and Oleson (1986) measured velocity fluctuations of 10 to 15% on time scales from 2 to 10 days on Daugaard-Jensen Glacier, including an event corresponding to the drainage of an ice-dammed lake that caused a velocity increase of more than 50% over 12 to 18 hours. Weidick (1988) described occurrences of surging in 26 locations in east Greenland between Daugaard-Jensen and Kangerdlugssuaq glaciers. These results suggest that important short-term variations in speed are possible, casting doubt on the long-term significance of velocities derived from radar interferometry on images only a few days apart. Here we report on first results from a feasibility study to evaluate the potential for using DISP images to obtain speeds on fast-moving outlet glaciers over longer time intervals of a few months or more.

KANGERDLUGSSUAQ GLACIER

The glacier selected for our pilot study is Kangerdlugssuaq Glacier in southeastern Greenland (Fig. 1). A number of recent studies has documented large changes occurring in this region, suggesting that the southeastern drainage basins of the ice sheet may be out of balance. By comparing the estimated mass input from snowfall with the output mass flux from ice flow along the 2000 m surface elevation contour, Thomas and Csathó (1999) computed the eastern ice sheet south of Angmagssalik to be thinning by ~30 cm/yr; this rate is approximately half the total annual accumulation over the study area. Repeat aircraft laser-altimeter missions in 1993 and 1998 over Kangerdlugssuaq Glacier revealed thinning rates of several meters per year (Krabill et al., 1999). Comparison of positions of calving fronts on Landsat images and maps compiled from aerial photography indicates that Helheim Glacier, Midgård Glacier, and Fenris Glacier near Angmagssalik all have retreated significantly since 1933 (Weidick, 1995). These results are consistent with a recent analysis of Seasat and Geosat altimetry data by Davis et al. (1998) showing that the mass balance is strongly negative for the ice-sheet interior east of the ice divide, both south of Angmagssalik and north of Kangerdlugssuaq.

Kangerdlugssuaq Glacier is among the fastest glaciers in the world, with a velocity reaching ~5 km/year (Dwyer, 1995), draining an interior basin of approximately 50,000 km^2, based on elevations derived from satellite radar altimetry (Bindschadler et al., 1989). The glacier is laterally constrained by fjord walls located about 5 km apart, and the large speeds are the consequence of convergence of ice from the large drainage basin into the narrow fjord orifice. The annual calving flux is estimated at ~15 km^3 per year (Reeh, 1985).

DECLASSIFIED INTELLIGENCE SATELLITE PHOTOGRAPHS

Image Acquisition

Over 860,000 images acquired by the first generation of the U.S. photo-reconnaissance satellites between 1960 and 1972 were declassified in 1995, thanks in part to the efforts of U.S. Vice President Albert Gore. All of the available high-resolution images in east Greenland were acquired by the KH-4A system. Each image covers an area of approximately 10.6 × 144 nautical miles (19.7 × 267.1 km). Neighboring images in a swath overlap by ~10%, enabling co-registration of adjacent images. Images are available as 3" × 26" (7.7 × 67.1 cm) positive films from the U.S. Geological Survey Earth Resources Observation System (EROS) Data Center at a cost of $18 per film. During the KH-4A mission 52 satellites were launched between August

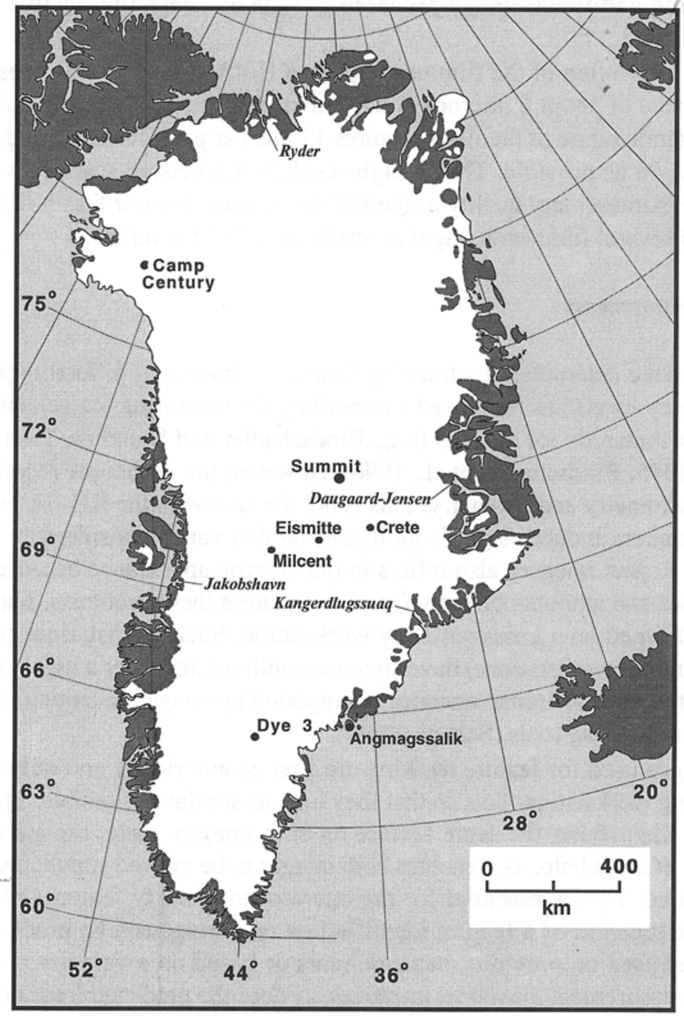

Fig. 1. Location map.

1963 and September 1969, with orbital inclinations and altitudes that varied from mission to mission depending on the desired coverage. Because the individual missions were rather short (typically less than 19 days) the available imagery over Greenland was derived from a number of different missions. As a result, images of the same area may look different because of differences in sun illumination angle, orbital geometry, and geometrical distortions of the panoramic camera.

Image Scanning

Determining accurate velocities by feature tracking requires that image pairs be radiometrically as similar as possible, and that camera distortions and differences resulting from orbital geometry be removed. To facilitate this process, photographs need to be digitized. In digitized form, the images can be most accurately co-registered and additional image processing, such as enhancing visible details, is greatly facilitated.

The best resolution of the film used by the KH-4A system is 120 lines/mm. Ideally a pixel size of about 8 microns is needed to preserve this resolution. Moreover, the high dynamic range of the films requires 12 bits per pixel for rendering as faithful a representation as possible. Thus a high-resolution precision scanner is needed to preserve the extraordinary quality of the KH-4A images. For our feasibility study, we had scanned several films with a spatial resolution of 12.5 microns.

Velocity Measurements

Velocities are determined by tracking features in images of different epochs. Correlation of grey levels has been used successfully for measuring ice velocities on fast moving west Antarctic ice streams (e.g., Bindschadler and Scambos, 1991; Whillans and Tseng, 1995; Bindschadler et al., 1996). However, this technique requires images of similar radiometry and geometry. This is not the case with the KH-4A images. The panoramic camera induces significant distortion that varies considerably within the image strip. Repeat imagery also differs in radiometric appearance because of different sun angles and amounts of snow cover. To address these problems, feature tracking was performed on a Leica softcopy workstation. Such workstations (essentially high-end graphics workstations) have stereo capabilities and offer a highly interactive environment where the human operator is supported by image processing, 3-D visualization, and measuring tools (Schenk, 1995).

The images used for feature tracking are first geometrically and radiometrically adjusted using workstation tools so that they look as similar as possible. The operator then begins identifying the same feature on both images. Here, the stereo display capability is of great help, as it enables both images to be viewed simultaneously or in short sequence. This is essential for the operator to identify features reliably and quickly. The location of a feature identified on one image can be predicted on the other image based on previous measurements or based on a velocity model. With every new measurement the model improves, as does the predicted location.

RESULTS

We purchased and had scanned several cloud-free images acquired on June 23, 1966 and September 24, 1966. The images then were adjusted radiometrically to facilitate identification of the same features, and features in the two images were then tracked on the Leica workstation. Figure 2 shows the portion of the June 23 image covering Kangerdlugssuaq Glacier and its tributaries. Superimposed on the image are the velocity vectors obtained from measuring the image position of the same feature in both images. A magnified view of two features labeled A and B in Figure 2 is shown in Figure 3 for both the June 23 and September 24 images, to demonstrate that even after contrast adjustment considerable differences in both images remain, making feature tracking a challenge.

The velocity vectors were measured on co-registered images and transformed into a UTM projection system. For the image-to-image and the image-to-map registration, eight stationary points on rock outcrop (indicated by crosses in Fig. 2) were

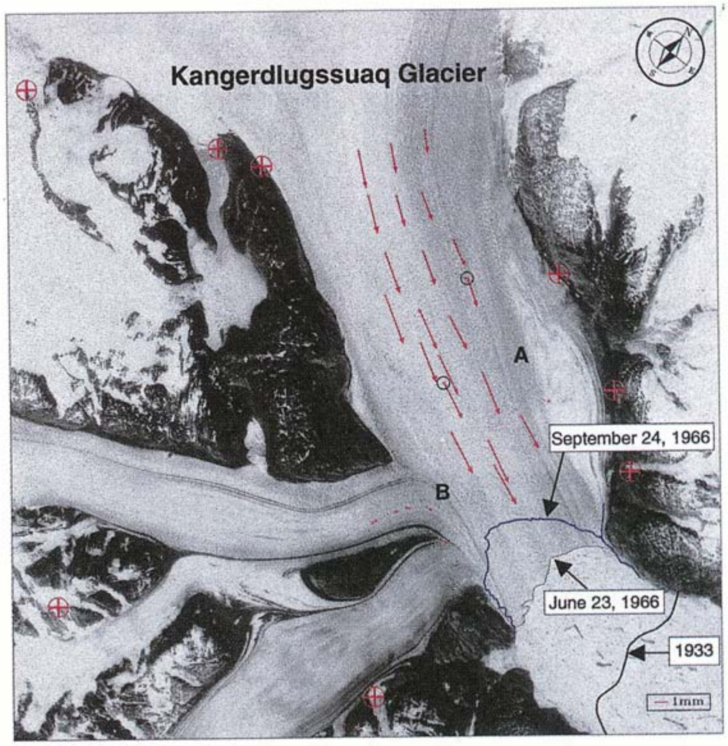

Fig. 2. DISP image of Kangerdlugssuaq Glacier, east Greenland, obtained on June 23, 1966. Arrows represent velocities determined from feature tracking, and circled crosses indicate control points used to co-register the June 23, 1966, and September 24, 1966 images. Scale at bottom (1 mm) refers to the original film. Also shown is the position of the calving front on those images and from a map based on aerial photographs taken in 1933.

identified. Both transformations were approximated by affine transformations, which is justified because of the relatively small area of the study region. The most detailed topographic map of the area (1:250,000 scale) was used for deriving the image-to-map coefficients. The final error in the velocity vectors consists of two components. The RMS error in image space is 0.09 mm and is mainly the result of the coarse approximation of the camera model by the affine transformation. Geocoding the co-registered images introduces another error that can be estimated from the variance of the covariance matrix of the transformation from image to object space. The error analysis rendered $60\sqrt{2}$ m as the accuracy of the geocoded displacement vectors. These displacements pertain to a time interval of 94 days, so the uncertainty in derived velocity is $365 \times 60 \times \sqrt{2}/94 = 0.33$ km/year.

In Figure 2, the longer vectors along the centerline of the glacier represent velocities of ~6 ± 0.33 km/year. This value is larger than the velocity reported by Dwyer (1995), who applied automated image cross-correlation techniques to three Landsat multispectral scanner and thematic mapper images acquired over a one-year period (1988–1989) to obtain surface speeds of Kangerdlugssuaq Glacier. Because of differences in crevassing and deformation, he could not determine velocities from the two images spaced 10 months apart. From the two images taken during the summer of

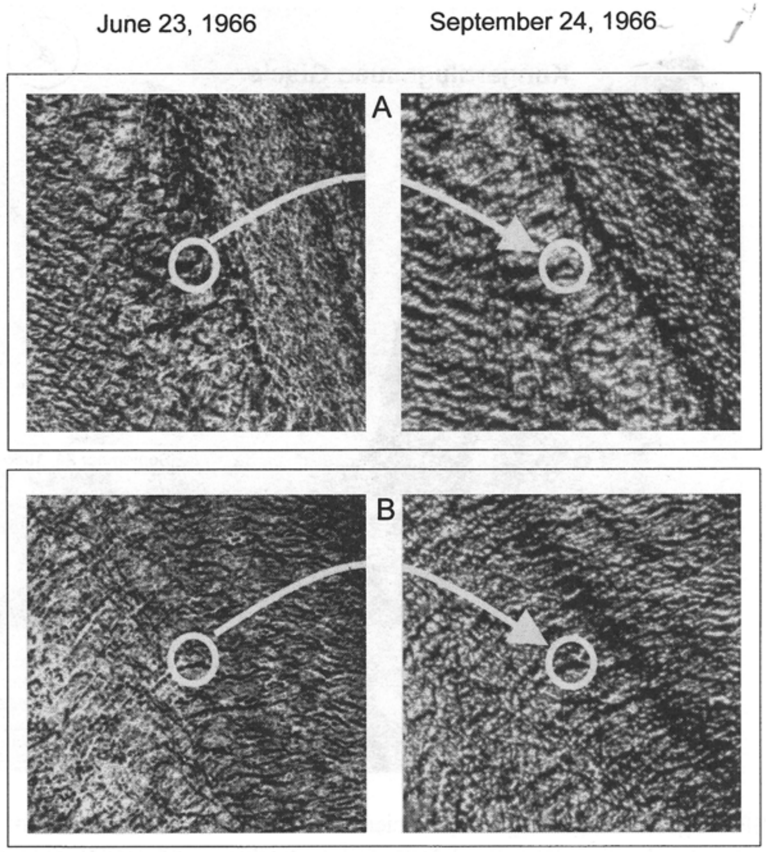

Fig. 3. Magnified view of the two features labeled A and B in Figure 2 on the June 23 and September 24, 1966 images.

1988, Dwyer (1995) determined a velocity in the ablation zone of ~5 km/yr, with an estimated error of 0.2 km/yr. However, Dwyer's value represents an average of 54 displacement vectors covering an area ~5 km long and 2 km wide that also includes slower-moving ice toward the glacier margins. Thus, it is not certain that the difference between our 1966 speeds and Dwyer's 1988 average value is significant and representative of a slowing of the glacier.

Comparing the geocoded KH-4A image and the 1:250,000 map compiled from a 1933 photogrammetric survey suggests that changes in the area have occurred between 1933 and 1966. Figure 4 shows that the calving front of Kangerdlugssuaq Glacier seems to have retreated significantly. This result is consistent with the finding of Dwyer (1995) that a significant loss of ice occurred in the terminus area from 1978 to 1991. It should be pointed out, however, that there are important seasonal variations in the position of the calving front (Dwyer, 1995; compare also the June 23 and September 24 positions shown in Figure 2), making it difficult to quantify the rate of retreat if only two terminus positions are compared.

In addition to changes in the position of the calving front, it appears that all of the tributary glaciers on the eastern side of Kangerdlugsuaq Glacier retreated (indicated by the arrows in Fig. 4). On the 1933 map these tributaries are shown to join the main glacier, whereas the DISP image suggests that the tributaries now terminate on land.

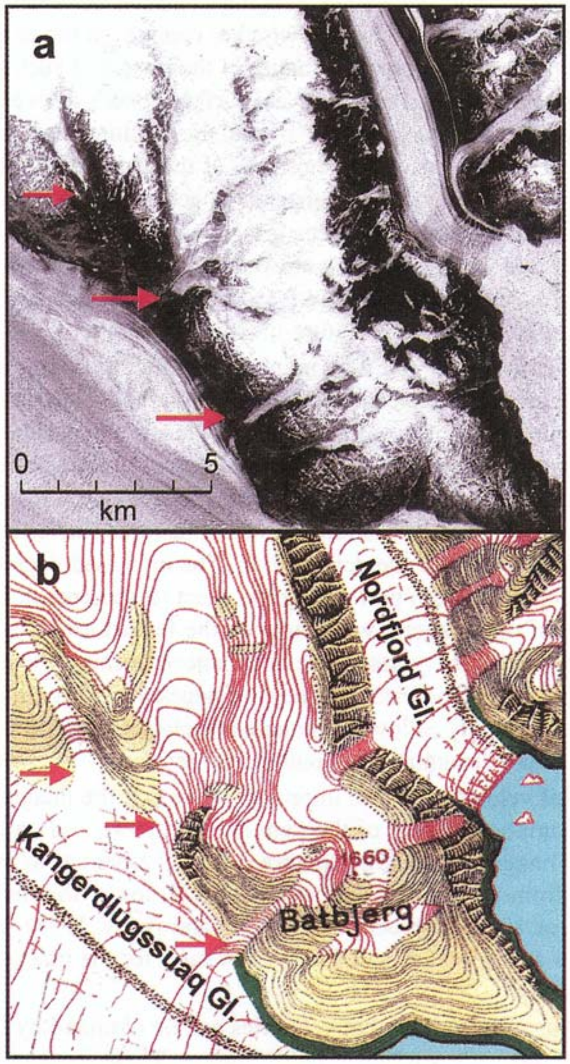

Fig. 4. The retreat of tributary glaciers on the eastern side of Kangerdlugssuaq Glacier between 1933 and 1966. The upper panel shows the June 23, 1966 DISP image and the lower panel the same area depicted on a Greenland Geological Survey map based on 1933 aerial photography. In both figures, arrows point to tributary glaciers that appear to have retreated.

However, without consulting the aerial photographs on which the map is based, it is not possible to evaluate whether the retreat is real or an artifact of how the 1933 map was compiled.

DISCUSSION

The main objective of this contribution is to demonstrate the utility of high-resolution DISP images for glaciological applications, in particular on fast-moving outlet glaciers draining the interior of the Greenland Ice Sheet. As demonstrated earlier by

Sohn et al. (1998) DISP allows detailed mapping of glacier boundaries, which can be compared against other sources to assess whether changes in the extent of ice cover have occurred. Further, the radiometric quality of the images is such that surface features can be tracked from epoch to epoch and surface speeds derived over relatively short time intervals. For the example shown here, the resulting error in speed is rather large (~0.3 km/year) as a result of the shortness of the time interval between images and because the images were not co-registered as accurately as possible. Because it was not clear a priori that velocities on this fast-moving glacier could be derived from DISP images collected only several months apart, we did not attempt to obtain the most accurate results. However, with the feasibility established, several suggestions can be implemented to improve the feature-tracking procedure.

The degree of automation could be increased by incorporating image-matching techniques (grey-level correlation and feature-based methods) into the process and we intend to explore this possibility in the future. Extensive experience with feature-based matching shows that image-matching techniques are much more robust than grey-level matching (Schenk et al., 1991; Toth and Schenk, 1992). An additional advantage is that the shape deformation of tracked features carries implicit information about the forces that cause the deformation. The increased degree of automation would release the operator from performing the exact measurement. However, owing to the complexity of the imagery, we anticipate the feature-tracking task to remain interactive. In this way, quality assurance is enhanced because the matching results are immediately displayed and can be rejected if necessary. This eliminates the cumbersome phase that typically follows automatic correlation procedures where the displacements are manually examined and outliers are removed.

The accuracy of velocities can be improved by basing the image-to-image registration on a mathematical model of the panoramic camera and on identical points measured in both images. A realistic camera model is essential to avoid systematic errors stemming from the camera distortion and will lower the image registration error to 0.02 mm, or 10 m in object space (Habib and Belay, 1998). The corresponding error in glacier speed would be reduced to 54 m/yr for the image pair considered in the feasibility study.

In summary, our results show that velocities can be obtained by tracking surface features on sequential high-resolution DISP images. These images are inexpensive and readily available, and can be digitized at relatively low costs. Thus, they constitute a valuable resource for glacier monitoring, allowing establishment of a 1960s baseline against which current and future changes can be compared.

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