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Digital comparison of high resolution Sojuzkarta KFA-1000 imagery of ice masses with Landsat and SPOT data

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ABSTRACT. Russian satellite imagery of the polar regions has recently become available to western scientists through Sojuzkarta. The KFA-1000 photographic camera is of particular interest to glaciologists due to its high resolution (a nominal 5 m). Digitized photographic products from this instrument are compared with digital data from Landsat and SPOT series satellites for a partly glacierized area of northwest Spitsbergen. Comparison of KFA-1000 data with detailed maps of man-made structures at the settlement of Ny Ålesund demonstrates that the resolution of the photographic imagery is about 3 m, but scanner resolution limited our digital data to about 6 m. Significantly less detail can be resolved on Landsat TM imagery and Landsat MSS data fail to resolve any of the structures. KFA-1000 data are compared with Landsat TM and MSS images and SPOT HRV multispectral imagery for several tidewater glaciers in Spitsbergen. KFA-1000 imagery is of a significantly higher geometric resolution than the other sensors, allowing the clear identification of individual crevasses and other ice surface features. KFA-1000 scenes from 1985 and 1988 are used to measure ice marginal fluctuations for several northwest Spitsbergen glaciers, and the onset of a surge can also be identified. This imagery has a 60% overlap between scenes and the heighting accuracy of the stereoscopic data is calculated at 45 m. Radiometric analysis of KFA-1000 data is restricted to relative brightness values, since no absolute calibration is available. The photographic products appear speckled, and the range and standard deviation of normalized pixel brightness values over snow is greater than for equivalent Landsat TM data. The very high spatial resolution of the KFA-1000 camera is its principal attraction for glaciologists.

INTRODUCTION

Russian satellite imagery, including data from ice-covered areas of the polar regions, has recently become available commercially through Sojuzkarta (Piskulin, 1989). One sensor of particular interest to glaciologists is the photographic camera KFA-1000, due to its very high spatial resolution (a nominal 5 m). Imagery of relatively high resolution, at visible and near-infrared wavelengths, has been available to latitudes of 81° N/S since the launch of the Multispectral Scanner aboard Landsat 1 in 1972. Over the period since then, the spatial resolution of satellite sensors producing both photographic and digital products has gradually improved, mainly through instruments deployed on Landsat and SPOT series satellites. Data from these sensors have been used to undertake a variety of glaciological investigations, including glacier mapping (e.g. Williams, 1986; Swithinbank, 1988), geometric measurements of ice surface topography (e.g. Dowdeswell and McIntyre, 1987), glacier velocity (e.g. Lucchitta and Ferguson, 1986; Bindschadler and Scambos, 1991), glacier terminus fluctuations (e.g. Dowdeswell, 1986) and radiometric investigations linked to glacier mass balance (e.g. Orheim and Lucchitta, 1990).

In this work we investigate the utility of the Sojuzkarta KFA-1000 photographic camera as a tool for glaciological studies. Examples are presented of imagery from glaciers and ice caps in the Svalbard archipelago derived from the KFA-1000 camera (Fig. 1), and converted to digital form using a high-resolution digitizer. A comparison is undertaken between the geometric and radiometric properties of these data and those from other visible and near-infrared wavelength sensors of relatively high resolution.

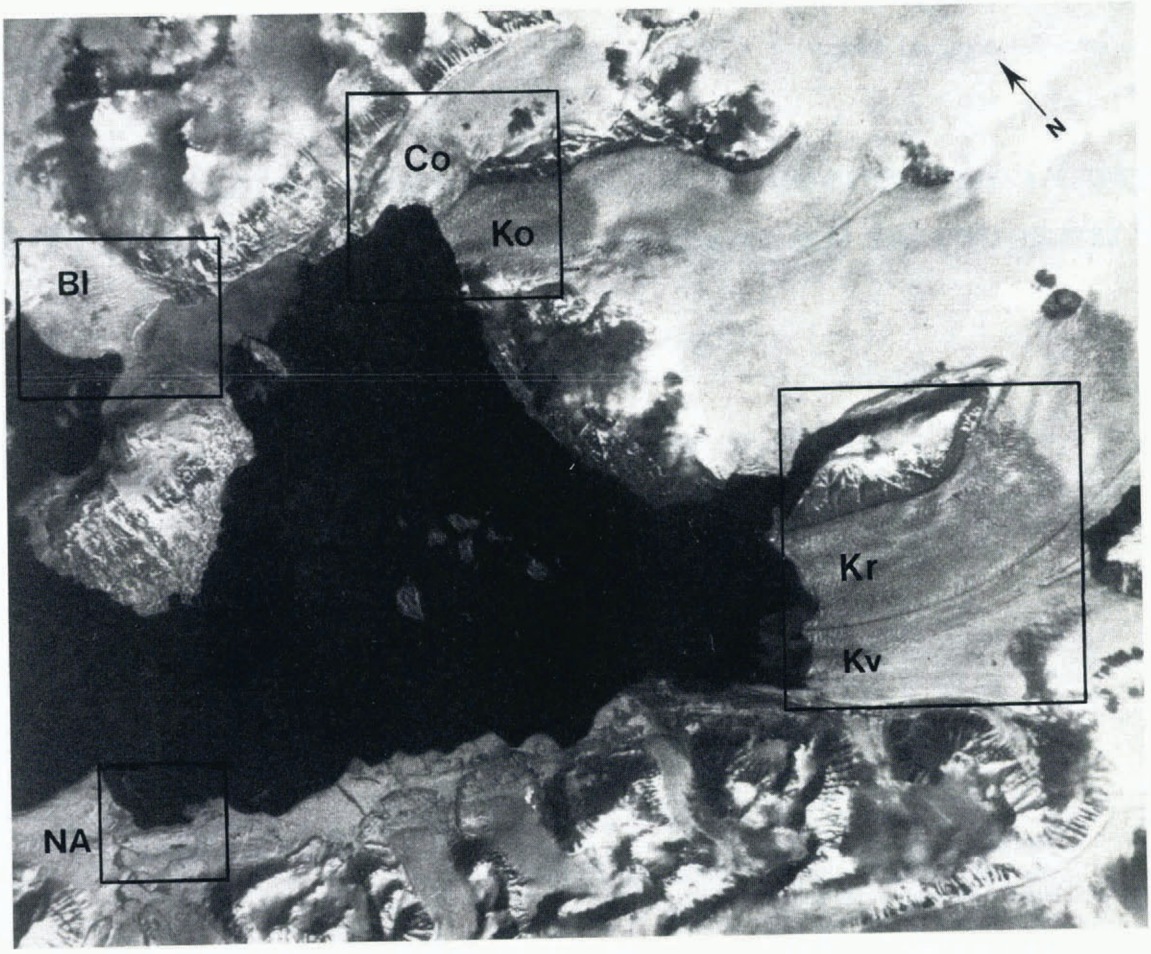

Fig. 1. Digital satellite image of the Kongsfjorden area of northwest Spitsbergen, acquired by KFA-1000 camera on 12 June 1985. Figures 2, 3, 4 and 5 are located as insets. NA is the settlement of Ny Ålesund, Bl is Blomstrandbreen, Co is Conwaybreen, Ko is Kongsbreen, Kr is Kronebreen and Kv is Kongsvegen. Scale bar is 5 km.

DATA SOURCES AND METHODS

KFA-1000 camera

KFA-1000 cameras (focal length 1000 mm, spectral range 570–680 nm and 680–810 nm) have been deployed aboard several Russian Cosmos-series satellites, orbiting at an average height of 270 km. This gives an average scale of 1 : 270 000 for photographs from the KFA-1000. Photographic frame size is 300 × 300 mm and the nominal area of ground coverage is, therefore, 80 × 80 km. Two cameras are mounted in each satellite, photographing a strip to either side of the sub-satellite track. These cameras are inclined outwards at 8° from the nadir direction. An overlap of 60% is present between successive images along track, providing considerable scope for stereoscopic analysis of ice surface topography. The Cosmos-series satellites, on which several KFA-1000 cameras have been deployed, have variable orbits, some of which reach to above 82° N/S, which means that coverage of all northern hemisphere ice masses and much of Antarctica is available in principle. Calibration standards and grey scales are not provided with each image, and so the potential for detailed analysis of radiometric data is limited to relative brightness levels.

To enable KFA-1000 photographic products to be compared in detail with digital data from the other sensors, black and white positives on film (produced directly from the original negative) were digitized using a high resolution Joyce–Loebl scanner at the Royal Aircraft Establishment, Farnborough, U.K. The resolution of the scanner was 25 μm, which gives the equivalent of 6 m resolution for a 300 × 300 mm film positive. This represents a slight undersampling of the full detail on the photographic product. We recommend the use of a 12.5 μm scanner in future work, in order to obtain the full resolution of the photographic imagery in digital form. Once the KFA-1000 data were transformed into computer-compatible tape (CCT) format, they were analyzed using standard image processing techniques on a Sun-based system.

It should be noted that a lower resolution camera, KATE-200, has been deployed on several Cosmos satellites, and its products are also available through Sojuzkarta. This camera has a focal length of 200 mm, and three spectral bands (500–600, 600–700 and 700–850 nm). The orbital height is 270 km, giving a scale of 1 : 1 350 000. Image frame size is 180 × 180 mm, producing ground coverage of 243 × 243 km per scene. The nominal resolution of these products is given as 15–30 m by Sojuzkarta, with the range in this value resulting from variations in the orbital height of individual satellites. We

Table 1. Details of digital satellite images of northwest Spitsbergen, Svalbard, examined as part of this study

Satellite instrument	*ID Number or path/row*	*Date imaged*
KFA-1000	2098-3-C 26781	12/06/85
KFA-1000	2098-3-C 26782	12/06/85
KFA-1000	2345-3-C 25892	12/06/88
Landsat MSS	213/004	28/08/86
Landsat MSS	218/003	05/05/84
Landsat MSS	219/002	21/07/83
Landsat MSS	219/003	27/07/83
Landsat MSS	238/002*	11/07/79
Landsat MSS	238/003*	12/08/78
Landsat TM	213/004	28/08/86
Landsat TM	215/004	31/08/88
Landsat TM	221/003	07/08/87
SPOT HRV-XS	152/040	08/09/86

* Path/row for Landsat 1–3 (all others for Landsat 4–5).

have obtained imagery of ice masses in Svalbard and Franz Josef Land from this camera, but only data from the higher resolution KFA-1000 are discussed in this paper.

Landsat and SPOT data

The spatial and radiometric properties of digital KFA-1000 data are compared with digital imagery obtained from the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and SPOT High Resolution Visible (HRV) sensors, available from our glaciological investigations of Svalbard ice masses. The specifications of the CCT-format images of northwest Spitsbergen examined in this study are given in Table 1.

Data from these instruments provide a range of spatial resolution against which to compare the utility of KFA-1000 imagery in glaciological studies. The Landsat MSS has a nominal pixel size of 79 × 56 m, the Landsat TM has 28.5 m pixels, and the HRV multispectral scanner carried aboard SPOT has 20 m pixels. Comparison between data from these instruments and digital KFA-1000 imagery was carried out using our in-house image processing system, based on a Sun SPARC station IPC.

GEOMETRIC INVESTIGATIONS

Spatial resolution of KFA-1000 imagery

In order to assess the spatial resolution of digitized imagery derived from KFA-1000 photographic products, features of known size and shape were examined before moving on to glaciological phenomena. KFA-1000 data

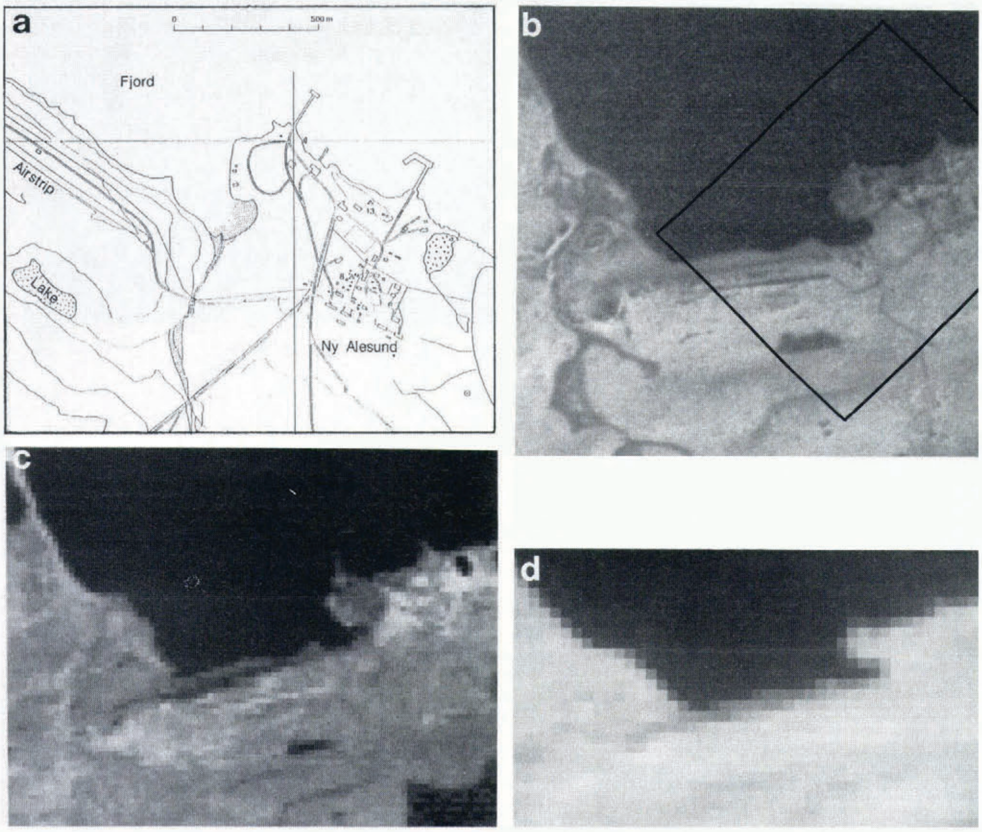

Fig. 2. Map and imagery of the Ny Ålesund settlement and surrounding area, northwest Spitsbergen (see inset in Fig. 1). (a) Map of buildings, roads, jetties and airstrip at Ny Ålesund (courtesy of Norsk Polarinstitutt). (b) KFA-1000 image, with the location of the map inset. (c) Landsat TM image. (d) Landsat MSS image. Note the distortion of image (d), due to the 79 × 56 m pixel size of the MSS. The images labelled (c) and (d) cover a similar area to (b). Scale bar is 1 km.

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imaging the man-made structures at the settlement of Ny Ålesund in northwest Spitsbergen were compared with 1:5000 topographic maps showing individual buildings, roads, air strip and jetties (Fig. 2a). The area of the settlement and its surroundings is also imaged by the KFA-1000 (Fig. 2b) and the Landsat TM and MSS (Fig. 2c–d). The airstrip, a lake and a number of roads and buildings are visible on the KFA-1000 imagery in Figure 2b. Close inspection of the film positives also shows that almost all the individual buildings shown in Figure 2a can be identified. We were able to resolve individual structures only 6 m in width, and spaced about 6 m apart, on the film positives. The pattern of these structures is close to the design of resolution test targets. This enables us to estimate that the resolution of the KFA-1000 products is on the order of 3 m, somewhat better than the nominal value of 5 m claimed by Sojuzkarta. Under favourable atmospheric conditions the spatial resolution can equal 2 m, according to tests by the American Institute of Aeronautics and Astronautics (Baxter, 1991).

The Landsat TM and MSS images shown in Figure 2c–d can resolve significantly less detail than the KFA-1000 photographic products. The lakes and jetties are visible in the TM scene, but the airstrip, roads and buildings are not resolved (Fig. 2c). In the MSS scene none of the above features is visible, and only the outline of the coast can be seen clearly (Fig. 2d).

It should also be noted that KFA-1000 imagery is suitable for stereoscopic analysis, in that adjacent scenes have an overlap of 60%. We have viewed two overlapping images acquired in 1985 (Table 1) in order to observe topographic effects qualitatively, but have not gone on to produce stereo-models of the terrain. The following simple expression may be used to calculate the heighting accuracy (Δh) of this stereoscopic imagery (Rees, 1990):

$$\Delta h = (2H\Delta h')/s \qquad (1)$$

where H is camera altitude, $\Delta h'$ is the accuracy of measurement of relief displacement on the film, and s is film width. With a nominal camera altitude of 270 km, an estimate of 25 μm for film measurement accuracy, and a film width of 0.3 m, the accuracy of height determination

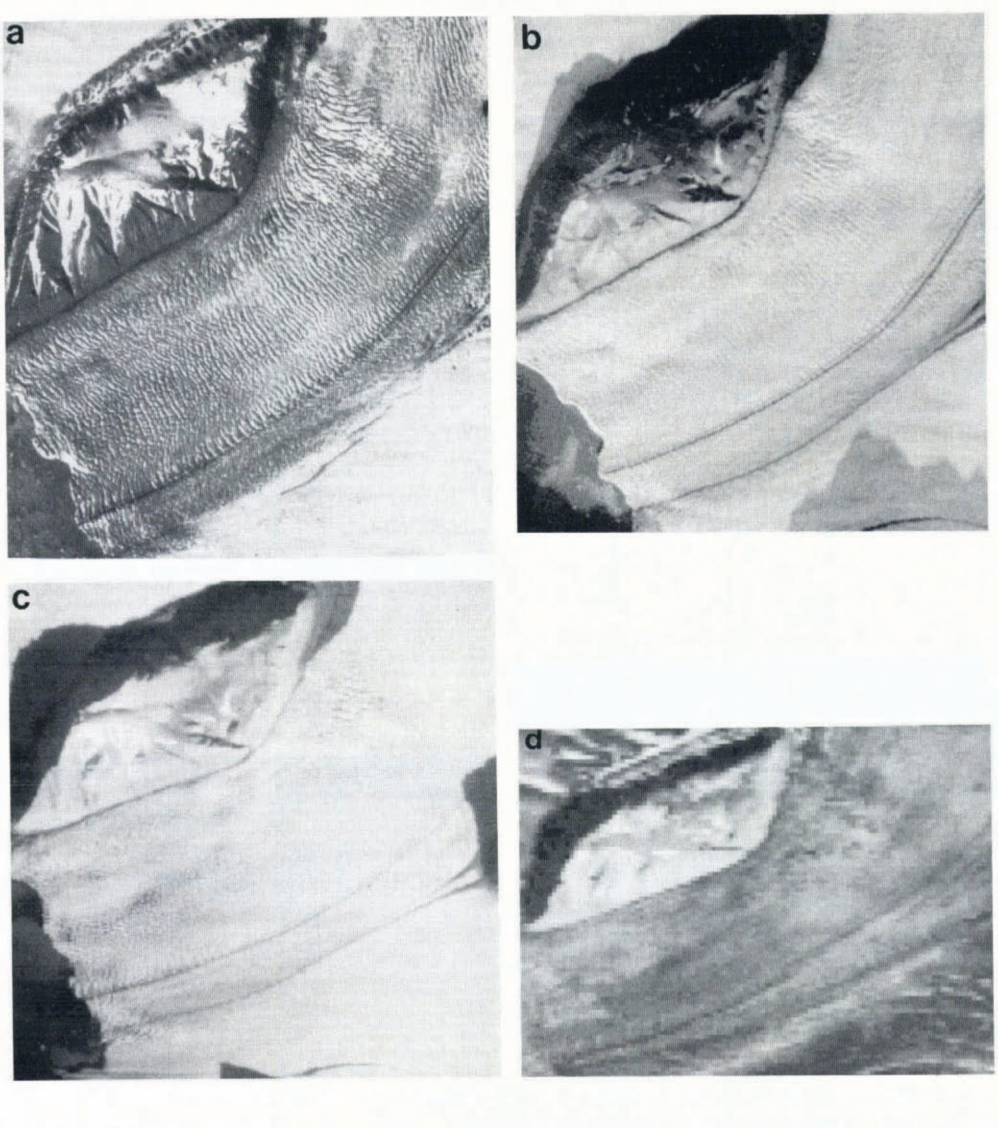

Fig. 3. The glacier surface of Kronebreen and Kongsvegen, and adjacent nunatak, northwest Spitsbergen (see inset in Fig. 1). (a) KFA-1000 image. (b) SPOT HRV-XS image. (c) Landsat TM image. (d) Landsat MSS image. Note the distortion due to the 79 × 56 m pixel size of the MSS. Scale bar is 1 km.

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is calculated as 45 m. We define film measurement accuracy by our choice of digitizing interval and take no account of film instability. This suggests that high relative accuracies should be obtained for local areas, but absolute errors will increase over larger regions due to the increasing effects of film distortion. Film distortion errors are likely to dominate over those associated with optical errors in the lens.

Comparison with glaciers imaged by Landsat and SPOT

The spatial resolution of digitized KFA-1000 imagery was compared with that from Landsat and SPOT sensors by producing sub-scenes of a similar area from each instrument at very much enlarged scales. The area used for comparison was the terminus region of Kongsvegen and Kronebreen, tidewater glaciers in northwest Spitsbergen (Fig. 1). This location was selected for study because it is fast-flowing, highly crevassed and has a number of medial moraines, providing easily recognized glaciological features for intercomparison. We are also familiar with this glacier system through our own field studies (e.g. Dowdeswell and others, 1984; Hagen and Saetrang, 1991).

Digital enlargements of the tidewater glacier termini imaged by the KFA-1000, Landsat MSS, Landsat TM and SPOT multispectral scanner are shown in Figure 3. The fine resolution of the KFA-1000 means that, at the scale of reproduction used here, individual pixels cannot be seen (Fig. 3a). This allows the straightforward identification of ice surface features such as crevasses and medial moraines. Several icebergs can also be resolved at the bottom left of Figure 3a, in the marine waters beyond the terminal ice cliffs of the tidewater glaciers. By contrast, the 79 × 56 m resolution of the Landsat MSS means that pixels show up clearly, whereas ice surface detail is less apparent (Fig. 3d). Crevasses and mountainside gullies cannot be identified on the MSS image. The SPOT and TM images, with 20 m and 28.5 m pixels, respectively, are intermediate between these two extremes (Fig. 3b–c). Crevasses are, however, noticibly better resolved on the SPOT image (Fig. 3b), whereas the effect of individual pixels is more apparent on the TM sub-scene (Fig. 3c). Visual comparison of the mountain at the top left of each image in Figure 3 also illustrates the decline in resolving ability through the four sensors clearly.

Glacier fluctuations and surges

An important use of satellite imagery is to provide time series of data on glacier marginal positions, which can then be related to climate change or, as in the case of glacier surges, to changes internal to the ice mass itself. The digital superimposition of glacier margins imaged several years apart by the KFA-1000 and the other imagery used in this study allows a ten-year series of ice marginal fluctuations to be recorded (Table 1). The relatively large pixel size of the Landsat MSS, with an error term of approximately 160 m (i.e. ±2 pixels) in the location of the ice margin (cf. Dowdeswell, 1986), implies that it is useful only when relatively large shifts in

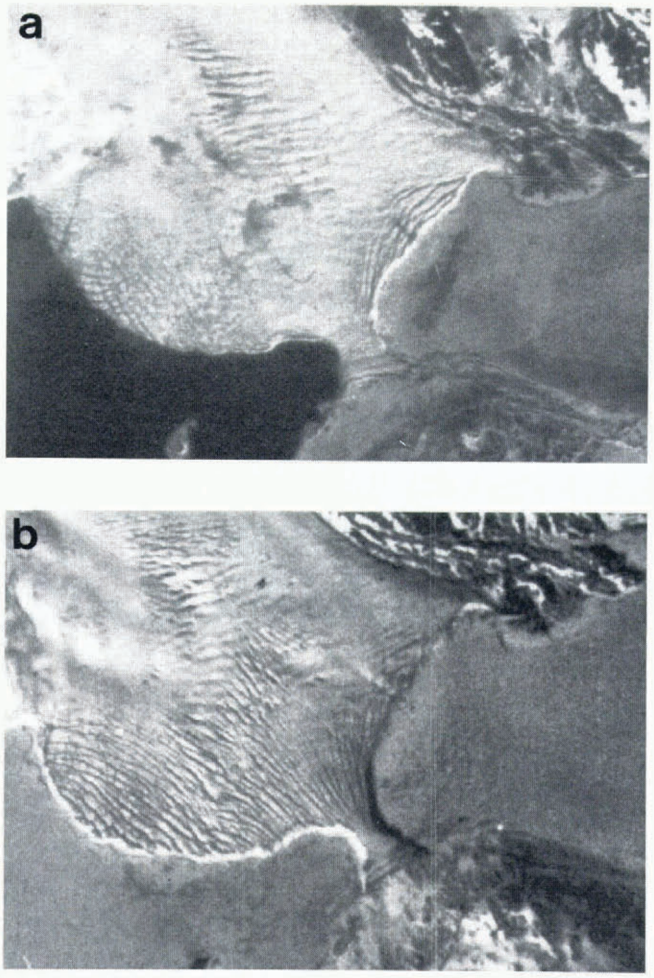

Fig. 4. KFA-1000 images of the tidewater terminus region of Blomstrandbreen, northwest Spitsbergen (see inset in Fig. 1). (a) 12 June 1985; (b) 12 June 1988. Fast ice covers the sea in (b) and the righthand part of (a). Scale bar is 1 km. Note the narrowing of the isthmus of ice attaching the glacier to the peninsula.

terminus position have taken place. A similar error term of ±2 pixels for KFA-1000 imagery would yield a value of ±12 m. The high resolution of KFA-1000 products, by contrast, makes them a particularly appropriate tool for investigating glacier terminus fluctuations. The ability to superimpose digital data from several satellites means that the digitized Sojuzkarta data can be integrated with existing high resolution satellite imagery to enhance time series of ice marginal positions.

Two examples illustrate the utility of KFA-1000 imagery in measuring and monitoring changes in the position of glacier margins. In Figure 4 the terminus region of Blomstrandbreen is shown on the same day in 1985 and 1988. This glacier has been retreating since a surge in 1960, when it advanced some 600 m (Liestøl, 1988). Retreat since that date has lead to the development of an increasingly narrow isthmus of ice attaching the parent glacier to the peninsula of Blomstrandhalvøya (bottom right in Figure 4). Measurements taken from the June 1985 and 1988 imagery of the area (Fig. 4) show that the isthmus of ice has narrowed by 230 m over this period. If the same rate of change, about 80 m a^{-1}, were to

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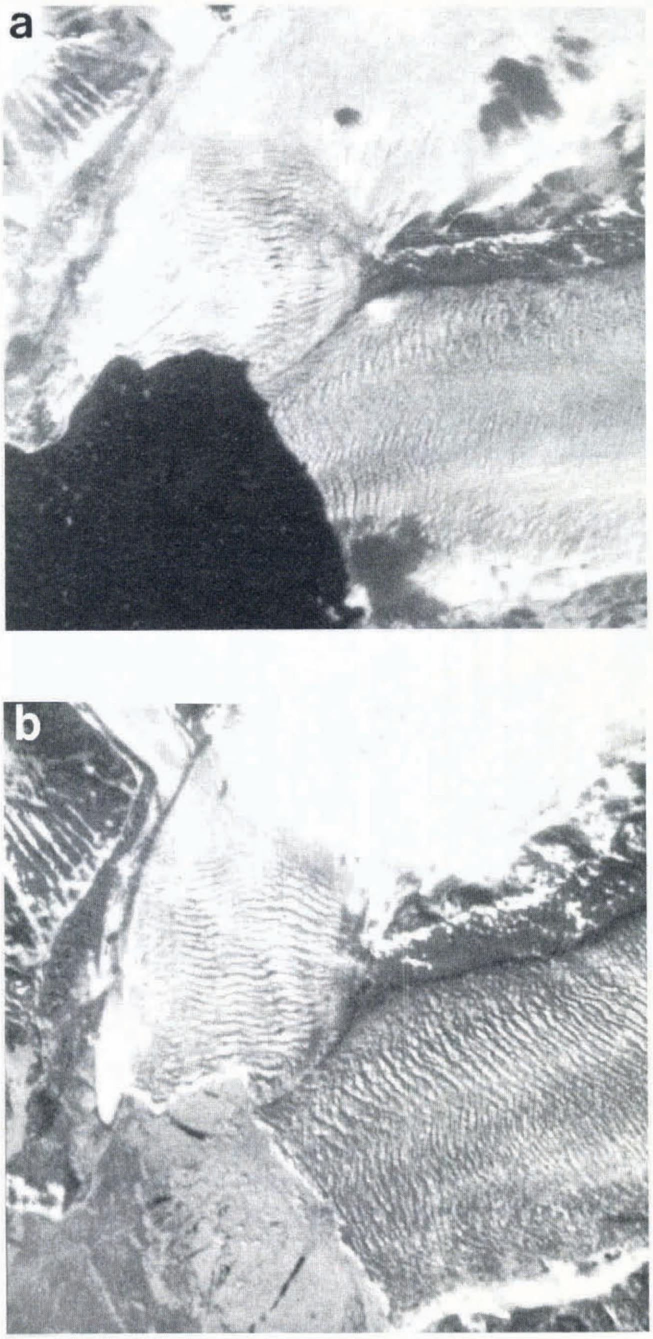

Fig. 5. KFA-1000 images of the lower parts of Conwaybreen and Kongsbreen, northwest Spitsbergen (see inset in Fig. 1). (a) 12 June 1985; (b) 12 June 1988. Note the icebergs embedded in fast ice in (b). Scale bar is 1 km.

continue, the remaining ice isthmus (200 m wide in 1988) would be predicted to disappear in a little less than three years. The ice was in fact breached by the sea early in 1991.

A second example of the utility of KFA-1000 imagery concerns two other tidewater glaciers entering Kongsfjorden, Conwaybreen and Kongsbreen (Fig. 1). Comparison of the ice marginal positions of these two glaciers in 1985 and 1988 imagery (Fig. 5) indicates that Conwaybreen retreated by up to 190 m over the period, whereas Kongsbreen advanced by up to 100 m. The differing sign and magnitude of ice marginal fluctuations on these adjacent glaciers is a significant finding. However, changes of this order are certainly beyond the spatial resolution of the Landsat MSS and would be detected only with a significantly lower accuracy through the analysis of Landsat TM and SPOT multispectral data.

The active phase of the surge cycle on surge-type glaciers can also be identified from KFA-1000 data. The high resolution of the KFA-1000 allows the identification of individual crevasses and, hence, both the initiation of the active phase of the surge cycle and the propagation of the surge front. The KFA-1000 imagery from 1985 and 1988 which we have obtained (Table 1) includes the tidewater glacier Osbornebreen, which began to surge during the 1986–87 winter (Dowdeswell and others, 1991). The change from a relatively smooth to a highly crevassed ice surface between 1985 and 1988 can be seen clearly on KFA-1000 images from these dates, along with changes in the glacier terminus position.

Several studies have also used Landsat imagery in order to obtain ice surface velocities (e.g. Lucchitta and Ferguson, 1986; Bindschadler and Scambos, 1991). However, due to the lower resolution of the Landsat MSS and TM in particular, the method has been restricted largely to the parts of major ice sheets flowing at hundreds of metres per year. The significantly higher resolution of KFA-1000 imagery means that it can be used successfully in the measurement of velocities on smaller ice masses, and those with rates of flow of tens of metres per year. The technique is thus suitable for analyzing glacier velocities within the Svalbard archipelago, for example, where previously velocity measurements have been restricted to field surveys and the detailed study of sequential aerial photographs.

RADIOMETRIC INVESTIGATIONS

Radiometric analysis of digital KFA-1000 data is restricted to relative brightness values. This is because calibration standards and grey scales are not provided with each photograph. Absolute radiometric values cannot therefore be obtained, limiting quantitative comparisons between different KFA-1000 images and between KFA-1000 data and radiometric observations from other satellite sensors. The quality of brightness values across individual KFA-1000 photographs is also variable, and the speckled nature of the Sojuzkarta photographic products can be seen in the partly glacierized area of northwest Spitsbergen shown in Figure 1. This speckled appearance is illustrated clearly in Figure 6a, where a 1 km^2 area of an upland ice field in northwest Spitsbergen, Holtedahlfonna, is shown. The sub-scene corresponds to an altitude of approximately 500 m on the ice field, an area which would certainly be snow-covered and therefore of relatively uniform brightness in June, the time of year that the image was acquired. The speckled brightness of the Sojuzkarta photographs therefore represents noise.

Analysis of pixel brightness levels derived from KFA-1000 and Landsat TM digital data demonstrates the relatively poor radiometric quality of the Sojuzkarta

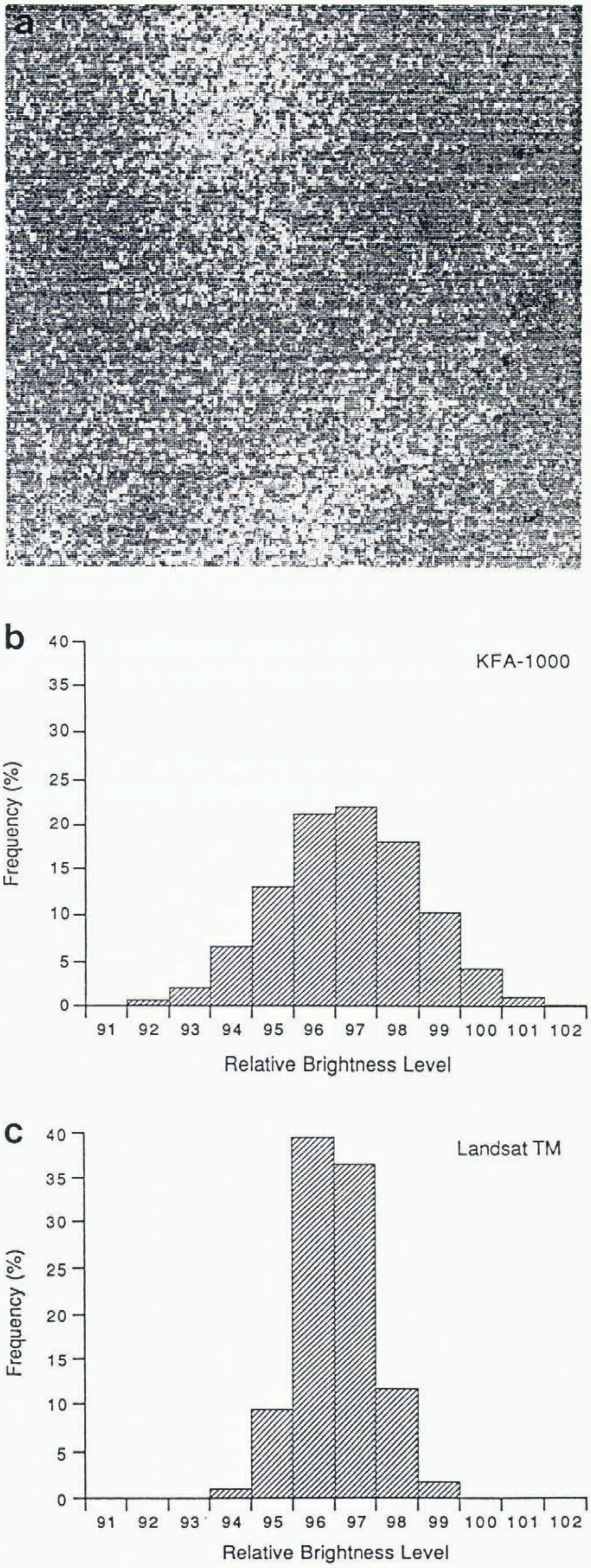

Fig. 6. (a) KFA-1000 image of a 1 km² area of the snow-covered surface of Holtedahlfonna, northwest Spitsbergen, showing the highly speckled nature of the photographic imagery. (b) Histograms of relative brightness levels for digitized KFA-1000 data and (c) Landsat TM data from the same 1 km² area of the ice field.

sensor more quantitatively. Histograms of pixel brightness sampled from the same 1 km^2 area imaged in Figure 6a are shown for the KFA-1000 and the Landsat TM in Figures 6b and 6c, respectively. These brightness values are normalized by taking account of the total range of pixel values found in the whole KFA-1000 image, which includes both snow-covered ice and much darker mountains and sea surface (Fig. 1), and the range in brightness for the corresponding area of the TM scene. Inspection of the histograms of relative pixel brightness shows that the range of values is significantly greater for the KFA-1000 data. In addition, the standard deviation of the KFA-1000 data is considerably higher than for the other instrument, indicating its poorer radiometric quality (Fig. 6b–c).

Despite these limitations to radiometric data from the KFA-1000, digitized pixel brightness values can be manipulated using image processing methods to enhance detail. Ice surface topography can, for example, be emphasized in glacier accumulation areas and in the region of ice divides (cf. Dowdeswell and McIntyre, 1987). Density slicing can also be used to pinpoint the position of the snow line during the melt season. A limitation here, however, is that data from different KFA-1000 images cannot be converted to real physical values (e.g. radiance, reflectance; Robinove, 1982), and each image must therefore be treated independently for classificatory purposes.

CONCLUSIONS

In conclusion, digitized KFA-1000 data from positive film products yield a high resolution digital dataset that can be readily integrated with digital Landsat and SPOT data products. This is important for obtaining detailed time series on, for example, glacier marginal fluctuations, including surging. The very high spatial resolution of the camera, confirmed by comparison with man-made structures of known dimensions, means that the data are also very suitable for the extraction of ice surface velocities. KFA-1000 imagery is of a significantly higher spatial resolution than data from the other visible band sensors examined (Landsat TM and MSS, SPOT-HRV-XS), allowing the clear identification of individual crevasses and other ice surface features. The availability of stereo-pairs as a standard product is also of some utility in the construction of stereo-models of ice surface topography, although heighting errors are approximately 45 m. The very high spatial resolution of the KFA-1000 camera is thus its principal attraction for glaciological users. The radiometric analysis of KFA-1000 imagery is restricted to relative brightness levels, because no absolute calibration data are available. KFA-1000 data also have high levels of radiometric noise relative to Landsat TM imagery. Nonetheless, ice surface topography and the position of the snow line through the melt season can be examined using KFA-1000 data products.

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