Geomorphic, Active Layer and Environmental Change Detection Using SAR Scene Coherence Images

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Abstract

Interferometric scene coherence images derived from synthetic aperture radar (SAR) data can reveal terrain morphology, stability, and highlight environmental changes. Regions of high phase correlation suggest terrain stability; regions of low phase coherence suggest physical changes have occurred at the scale of the radar wavelength. We consider coherence images of the Canadian High Arctic from tandem ERS-1/2 and repeat-passes of ERS-1 and RADARSAT-1. Large slopes reduce coherence, as is evident from ERS tandem data acquired with a 1-day interval. Other reductions in coherence can be accounted for by the accumulation or migration of snowdrifts and by compaction or re-crystallisation of the snow pack on the ground surface. In arctic environments, the scene coherence can reveal greater geomorphological detail than can be seen in SAR images or other optical data. As such, coherence images could be an important monitoring tool, especially during the winter months when snow cover and darkness impede observation with optical remote sensing methods.

1. Introduction

Synthetic aperture radar (SAR) interferometry from spaceborne satellite systems is a relatively new technique for retrieving elevation information and detecting dynamic changes affecting the Earth's surface. Application of these methods for supporting environmental monitoring objectives in the Arctic (Vachon et al., 1999) or other environments are far from fully developed. In this paper the *coherence image*, a derived product from a radar data pair, is introduced and examples are described from several localities (Figure 1) to illustrate its potential to provide terrain information.

2. Radar Coherence Images

For radar data sets with an appropriate baseline, scene coherence provides an estimate of the changes in electrical and physical properties of the ground over the resolution of the sensor and at the scale of the radar wavelength. Over the interval of time between two data acquisitions, small changes in these properties are not necessarily apparent in detected images, normally dominated by the amplitude of radar backscatter. The phase component of the complex backscatter value, however, can be used to advantage. The phase measurement from a single

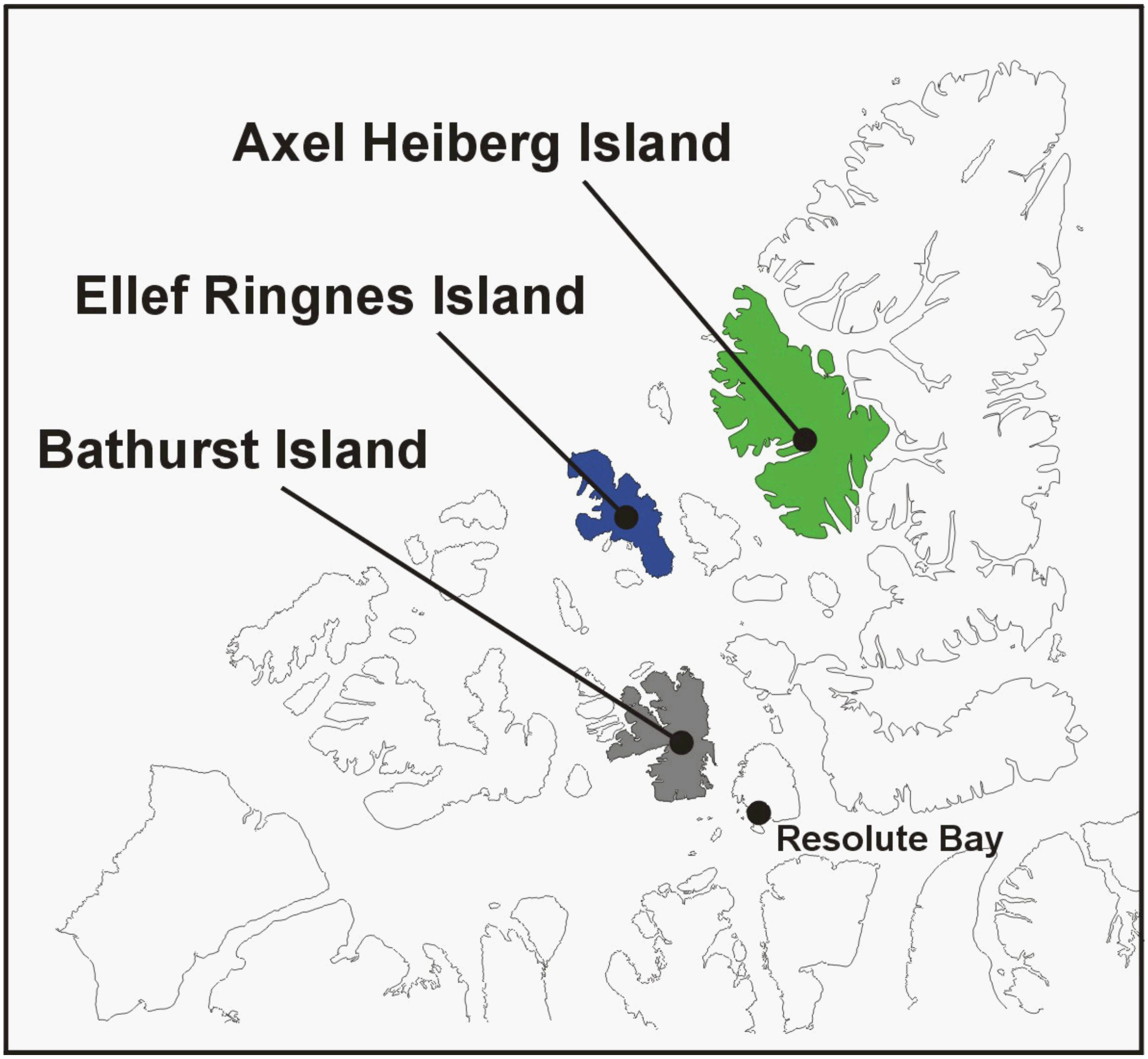

Figure 1: Location map of coherence images from the Canadian Arctic archipelago.

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radar observation is not by itself a useful parameter, but with knowledge of the satellite positions the phase difference between two radar observations can be computed (*e.g.* Goldstein et al., 1988; Li and Goldstein, 1990). Over a neighbourhood of pixels, the spatial variability of this phase difference is a measure of similarity of the terrain, also defined as the degree of coherence. To map the spatial distribution of the degree of scene coherence, an image of this parameter (0 to 1) can be created (Rignot and van Zyl, 1993; Hagberg et al., 1995; Vachon et al., 1995), which we shall term a coherence image.

Coherence images are generally displayed in gray scale where bright tones (values near 1) correspond to areas of high phase correlation. In these areas, few (if any) changes have occurred to the target area during the interval of time between data acquisitions. Regions of the coherence image represented by darker tones (values near 0) indicate where phase is largely decorrelated. The loss of phase coherence is the summation of all target and non-target related factors. Some non-target sources include the system signal-to-noise, viewing geometry of the radar system and SAR processing [1]. Geometrical effects related to the viewing geometry of the SAR imaging system in relation to the topographic relief can result in low coherence even if there is no physical change in the scene (Vachon et al., 1995). Areas with large slope gradients with respect to the radar incidence angle best illustrate this effect, as shown in Figure 2.

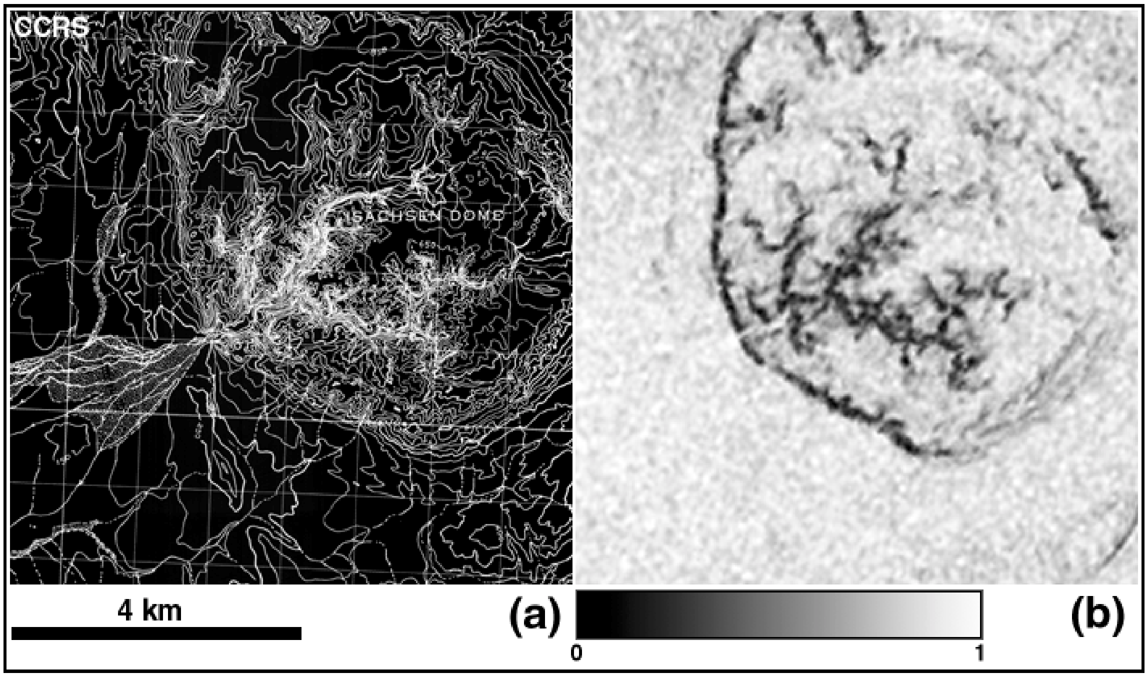

Figure 2: Isachsen Dome, Ellef Ringnes Island. (a) 50' contour intervals (in white) delineate steep topography along a deeply incised drainage network. (b) Coherence image of a 1-day tandem ERS-1 (9-Dec-95) and ERS-2 (10-Dec-95) data pair. Look direction is toward the right (ascending orbit pass). Low coherence occurs along zones of steep topography and is not likely caused by physical changes over the 24 hour period between acquisitions.

If suitable image pairs can be found with minimal non-target phase-loss effects, then coherence images can be used accordingly to recognise terrain related factors.

3. Terrain Sources of Phase Decorrelation

For a given area, the geometrical effects present in coherence images is dependent on the radar incidence angle and baseline between orbits (Vachon et al., 1995), but independent of the time interval between data acquisitions. Additional decorrelation caused by temporal effects can occur for a number of terrain, climatic or environmental reasons. The coherence images described below illustrate some contributing factors which cause phase decorrelation in Arctic environments.

[1] A discussion of the radar system and other effects contributing to the loss of phase coherence is beyond the scope of this work. The reader is referred to Armour et al. (1998) for additional information.

Over short intervals of time, such as single day tandem ERS-1 and ERS-2 data pairs, phase coherence is generally very high where vegetation is absent (Figure 3). Non-geometrical phase decorrelation identified in coherence images from these data pairs are generally indicative of short term temporal changes. For example, the sea surface exhibits low coherence due to tidal effects shifting the sea ice.

On land, some coherence loss may be attributed to snow fall or a redistribution of existing snow cover if wind speed is sufficiently high. There is little evidence of this effect in Figure 3, however a relatively isolated patch of very low coherence (labeled "B") is apparent. This phase loss is interpreted to result from a relatively rapid event affecting a continuous, but restricted area. The mountainous slopes in this area leads one to speculate that either a localized rock slide or avalanche occurred during this time interval. Field inspection of the area in July of 1998 showed that this sloping surface is characterized by very large (0.5 – 1.5 m) blocks, many of them perched on top of a surface of smaller cobbles and finer material. These blocks are not highly angular and thus do not appear to have been fractured from their source and transported great distance in the recent past. Their large size, however, does allow for the possibility that any amount of random movement or a localised rock slide could shift the blocks and change the scattering geometry. With relatively few large blocks occupying a single resolution cell, a large loss of phase can easily result.

Repeat-pass interferometry from archival ERS-1 and JERS or current ERS-2 and RADARSAT-1 satellite systems are able to provide radar data sets over time intervals greater than 1 day. For these data pairs, there is a better opportunity to detect changes in the distribution of snow cover or recrystallisation within the snow pack as well as slow, gradual ground movements related to active layer freezing. Subtle or steep depressions along drainage systems are topographic lows that are favourable for snow accumulation. In Figure 4, low coherence is identified along drainage channels, in stark contrast to the high coherence of felsenmeer, characterising much of the higher ground in the area. Accumulation, deflation or density changes due to compaction or recrystallisation in the snow pack along these channels are the most reasonable mechanisms to explain the loss of phase coherence (D'Iorio et al., 1996). In the RADARSAT-1 coherence image of Figure 5, similar drainage networks are recognized, but over the longer time span of 24 days, there appears to be an additional loss of coherence outside the drainage network. The broad, diffuse pattern of these features suggest a widespread change affecting the snow cover, such as new snow fall or possibly recrystallisation of accumulated snow. By inspection of the 12-day (Figure 4) and 24-day (Figure 5) coherence images, areas of high coherence are places which remain wind swept and snow-free or where no change in snow cover has occurred.

In the top part of Figure 4 (arrows at A), triangular patterns of low and high coherence are also evident. Across this plateau area, the pattern appears to be caused by strong winds from the N or NNW which have redistributed the snow cover. Drifting snow and ablation zones such as these are commonly observed across wide areas throughout the High Arctic. This is contrasted with areas of low coherence which outline where wind has deflated the snow pack or where drifts have accumulated. Coherence images provide information to recognise and monitor the movement and distribution of snow cover analogous to the observations made by Guo et al. (1999) on migrating sand dunes in arid regions of the Sahara desert.

The sedge meadow and swampy plain of Polar Bear Pass (B, Figure 4) is characterised by an overall loss of phase coherence. Geologically, the area is entirely underlain by fine grained Quaternary deposits, mainly marine and alluvial in origin (Kerr, 1974). It is possible that the

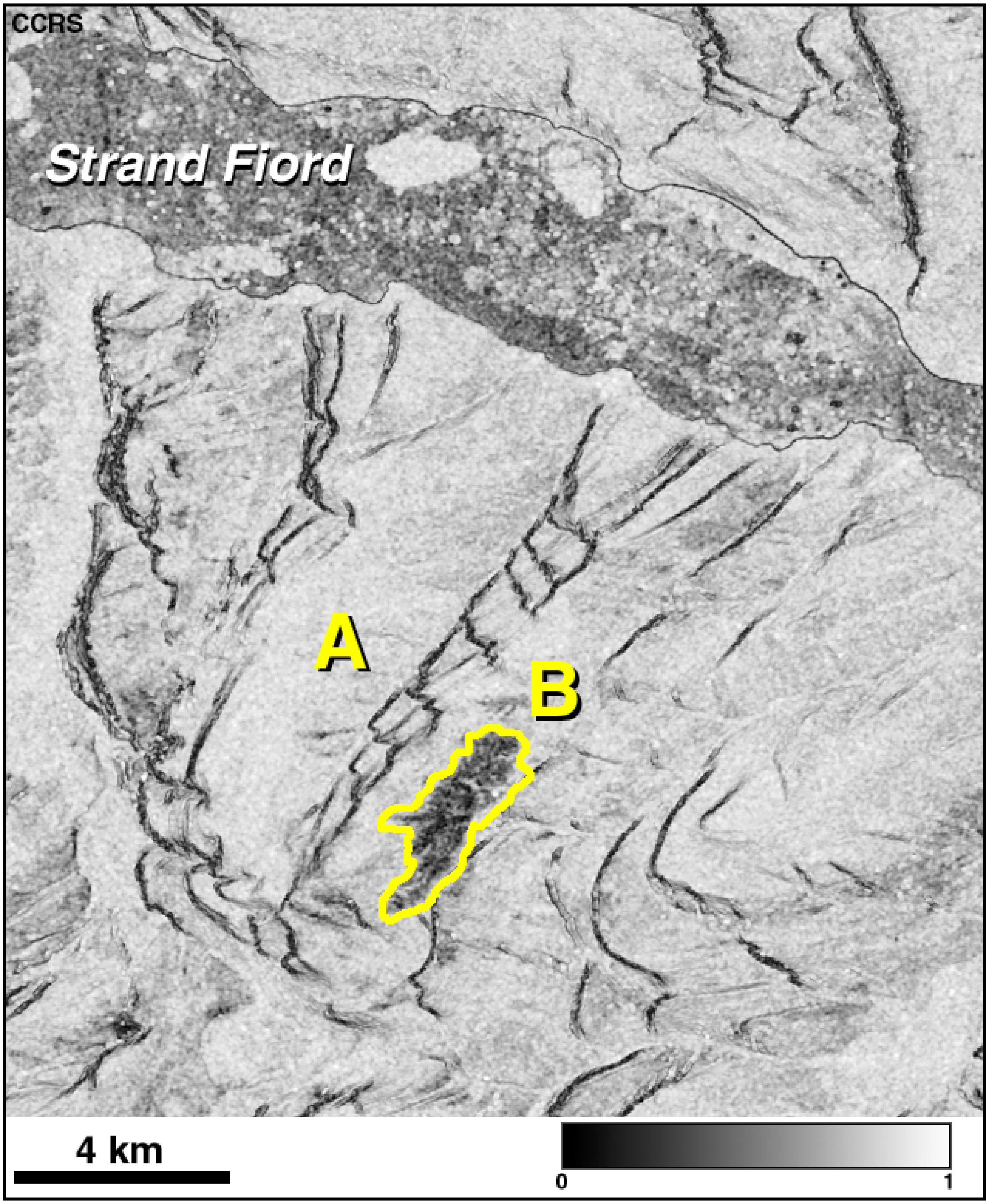

Figure 3: Strand Fiord, Axel Heiberg Island. Coherence image of a 1-day tandem ERS-1 (5-Dec-95) and ERS-2 (6-Dec-95) ascending orbit pair. Look-direction is toward the right. Dark linear zones of low coherence outline mountain ridges and steep topography in this region, indicating geometrical effects on phase loss. The back slope area of a range (A) shows good phase correlation and indicates stability of the surface. In contrast, a broad 4 × 1.5 km patch outlined (B) on the neighbouring slope, exhibits unusually high phase loss, a change likely caused by an extensive rock slide or snow avalanche.

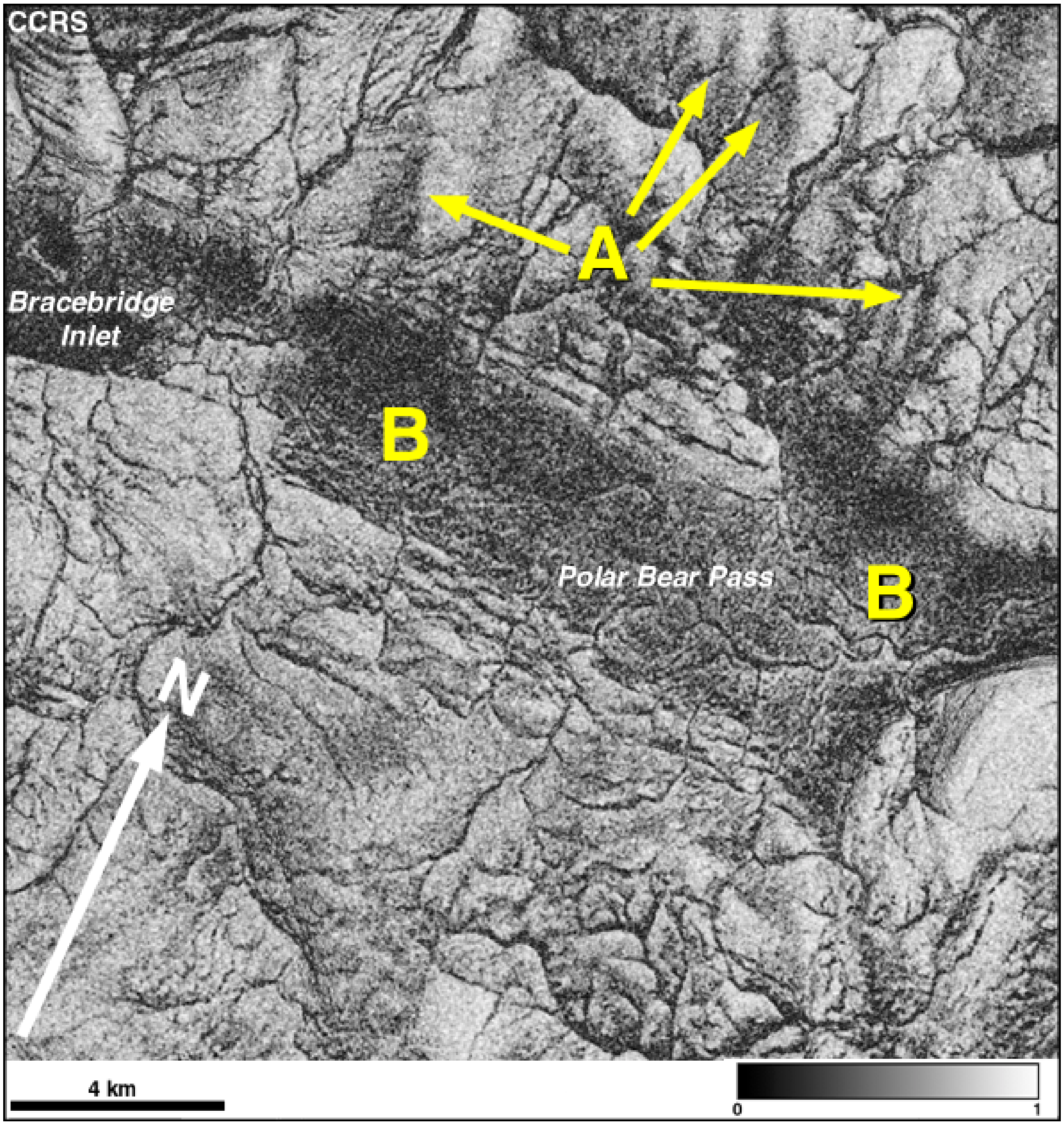

Figure 4: Polar Bear Pass, Bathurst Island. Coherence image of a 12-day interval repeat-pass ERS-1 ascending orbit pair (February 10 and 22, 1992). Drainage networks are clearly delineated in this image. Triangular patches of low coherence (A) outline areas where changes in the snow pack due to accumulation or deflation occur. The broad central area of low coherence (B) lies along a wetland of Polar Bear Pass.

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phase decorrleation is entirely due to snow accumulation over the wide low land, but freezing of the active layer and contraction of the ground occurs throughout the winter months (French, 1993). Small, incremental movements of the terrain within a resolution cell is a mechanism to account for some of the loss of radar phase coherence.

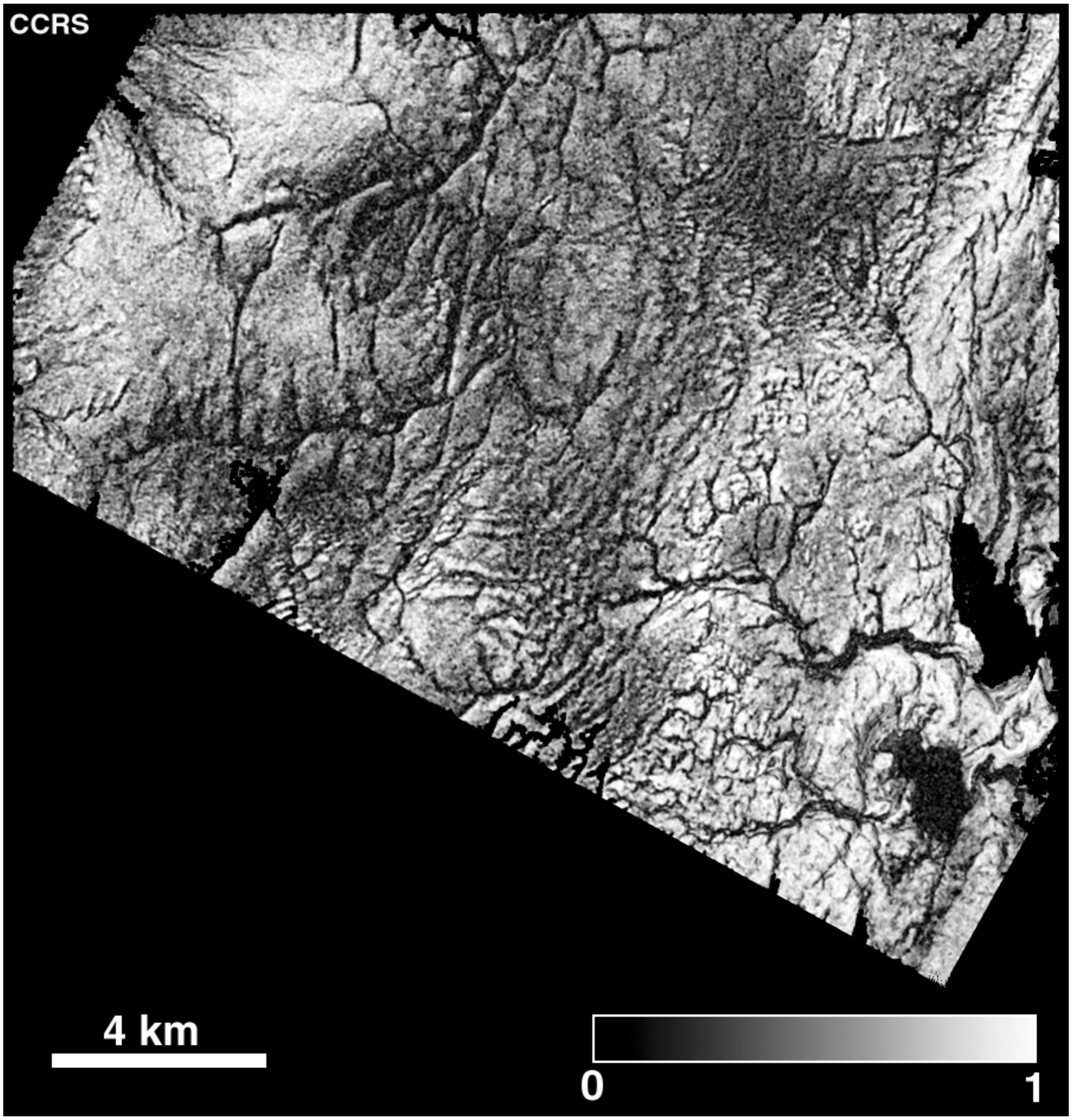

Figure 5: Bathurst Island. Coherence image of a 24-day interval repeat-pass RADARSAT-1 (F5) descending orbit pair (4-Mar-96 and 28-Mar-96). Drainage networks are clearly delineated in this image. Diffuse patches of low coherence throughout the image may represent changes in the snow pack of uncertain origin.

4. Discussion

The radar coherence image examples described in this study correspond to periods during cold winter months in the High Arctic when terrain stability is highest. The scattering properties of C-band radar are sensitive to the viewing geometry on steep topographic slopes, a change in the thickness or characteristics of the snow cover, and small terrain movements related to active layer processes. Phase decorrelation is a cumulative effect of all these factors and therefore coherence images can provide terrain and temporal change information.

Coherence images hold great potential as a tool for environmental monitoring. Detection of change in snow cover over specified time frames is demonstrated in this study, but the application for accurate snow cover mapping remains an area to explore. For geomorphic studies, great detail in the pattern and extent of drainage networks is revealed in coherence data which is not easily recognized from standard radar or optical imagery or available from hydrographic or topographic maps. Phase decorrelation is also identified with areas where small amounts of ground movement have likely occurred. This important observation raises the possibility that coherence images can be used to closely monitor the freeze and thaw behaviour of the active layer in cold climates.

5. Acknowledgements

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