Nunavut Terrain and Soil Analysis

Reference: 2010-69

Final Report

DRAFT

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Executive Summary

In order to better assess climate change risks to land development, the Government of Nunavut invited tenders (RFP 2010-69, 30 July 2010) for a desktop study utilizing radar satellite images to determine terrain suitability for future development in 14 communities in Nunavut. On 26 August 2010, an agreement for this study was signed with 3v Geomatics Inc. and BGC Engineering Inc. who together have extensive experience in remote sensing and permafrost respectively.. Nunavut, in partnership with Indian and Northern Affairs Canada, provided radar images to the project from the RADARSAT-2 satellite. In addition, Nunavut supplied aerial photos of the communities, optical satellite images, and other data such as elevation.

Between September 27 and October 4, 2010, 3v Geomatics and BGC visited the communities of Cambridge Bay, Gjoa Haven and Taloyoak for on-the-ground site inspections. Information from the site inspections was used in the detailed analysis of each of the 14 communities.

At least two RADARSAT-2 images were acquired over each community. 3vG and BGC processed these images and applied advanced radar image processing techniques and geotechnical analysis to produce the following input for each community:

- Motion layers
- Permafrost Features
- Low Areas
- Slope/Aspect
- Land Cover Classification

Based on these maps, permafrost and ground ice conditions were inferred and suitability maps created. These maps, which were produced for each community, divided development suitability into the following classification:

- No Data
- Suitable for development
- Possibly suitable for development
- Marginally suitable for development
- Unsuitable for development
- Built-up

The major limitation on the quality of the results of this study was the volume and timing of the radar images. In order to get good ground motion information from radar images, several images over the same area are required – ideally up to 10 to 15 images. In the Nunavut environment, these images need to be acquired in the summer months when there is no snow cover. The schedule for this study constrained the availability of good radar images.

The suitability maps created can assist in high level development planning, but should not be used for a detailed assessment of the foundation conditions. Remote sensing will only provide information on the ground surface characteristics and cannot provide information on the ground ice content, which is an important parameter in any northern foundation design.

The quality of the development suitability information could be improved by acquiring more RADARSAT-2 images over priority communities during the summer season. Longer-term comparisons (e.g. 2 – 3 years) will further provide a better appreciation for the dynamics in the landscape that is expected for all communities.

Contents

1.0 INTRODUCTION

Communities in northern Canada are facing significant challenges in expanding existing infrastructure due to the increase in ground temperatures, which results in degradation of permafrost. To date, no screening tools exist that would allow northern developers and regulators to assess terrain for potential developments in the future. In particular when considering climate change, it is important to know which areas may be regarded as suitable for development in the future and if special technical solutions have to be sought.

During this project, a methodology was developed to use remote sensing data combined with field expertise to determine development suitability. The project objectives were:

- establish a RADARSAT-2 image acquisition plan suitable for each community;
- use radar and optical satellites, and air photos to identify soil and surface conditions;
- develop terrain unit categories for classifying and ranking development suitability in the areas of interest surrounding each community; and
- use the data collected during the field visits to improve the classification.

The project mapped the development suitability at the following 14 communities (Figure 1):

1.) Cambridge Bay
2.) Chesterfield Inlet
3.) Rankin Inlet
4.) Baker Lake
5.) Hall Beach
6.) Sanikiluaq
7.) Gjoa Haven
8.) Coral Harbour
9.) Kugaaruk
10.) Taloyoak
11.) Repulse Bay
12.) Cape Dorset
13.) Kimmirut
14.) Pond Inlet

The permafrost distribution map shown in Figure 1 also indicates that all communities are located within the continuous permafrost zone.

A total of 60 RADARSAT-2 images were acquired and processed for this study.

This report details:

- Methodology applied
- All data inputs including data collected
- Results for each community
- Recommendations and conclusions

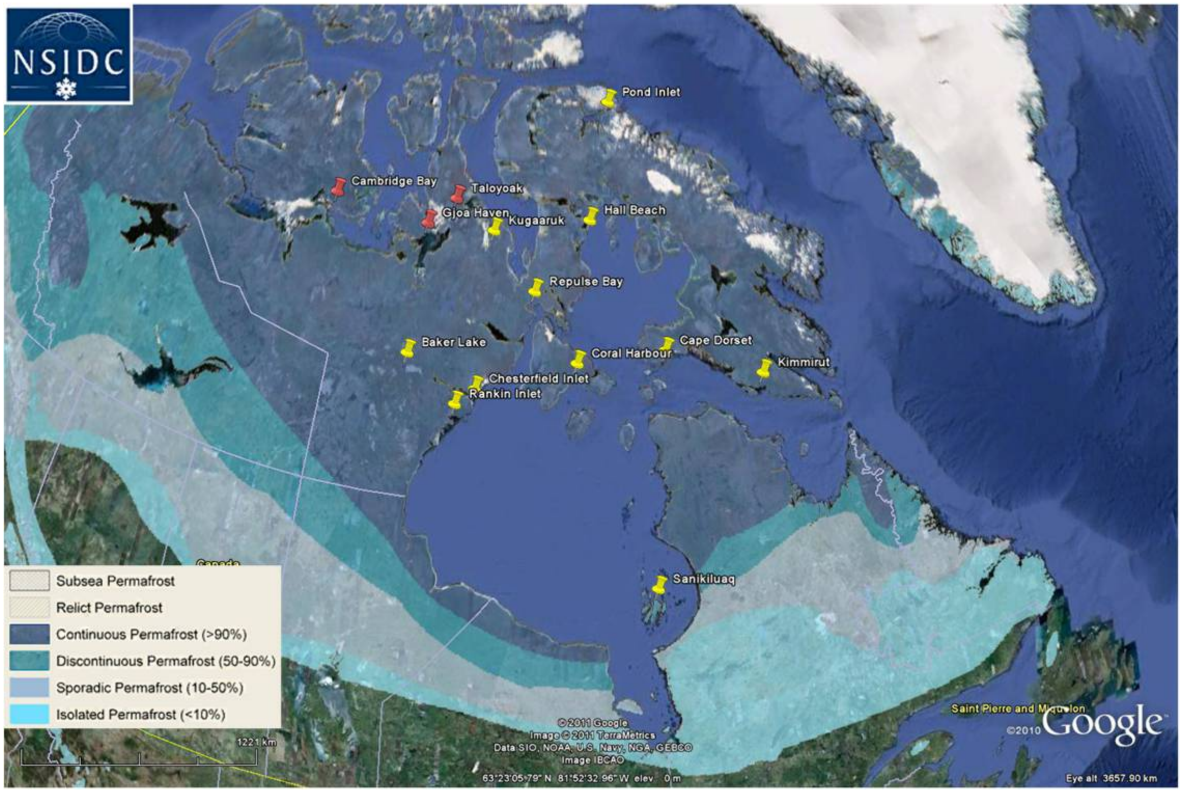

Figure 1 Overview of the communities investigated and the permafrost distribution. Red sites indicate the communities visited in Fall 2010

2.0 METHODOLOGY

Recent improvements in remote sensing techniques allow for rapid collection of various data on the earth's surface characteristics. However, in order to be able to judge suitability for development, subsurface conditions, such as the existence of ground ice are of importance. However, the ground ice content, which is likely the most important parameter for site selection, cannot be identified directly using remote techniques. Therefore, tools are required that allow correlation of surface characteristics with sub-surface conditions. The remote sensing techniques and supporting data used to identify and classify indicators of sub-surface conditions and provide permafrost data for interpretation are described in this section.

Optical and RADAR imaging systems are both mature technologies that aid in gathering land information remotely. Optical sensors are passive devices that depend on the sun to illuminate the land, and capture the light reflected from each ground target. They yield images that appear similar to those perceived by the human eye, and are suitable for characterizing land-cover, land-use, and ground features based on their colours, textures, and physical geometries. RADAR sensors are active devices that bounce microwave signals from the ground and measure the backscatter and path length of each target at the resolution, incidence angle, and frequency of the sensor. RADAR images were used to identify land cover types and for measuring subtle ground displacement.

3vG and BGC linked remote sensing features and knowledge of specific ground conditions, i.e. ice content, moisture, vegetation, and ground water salinity to map development suitability.

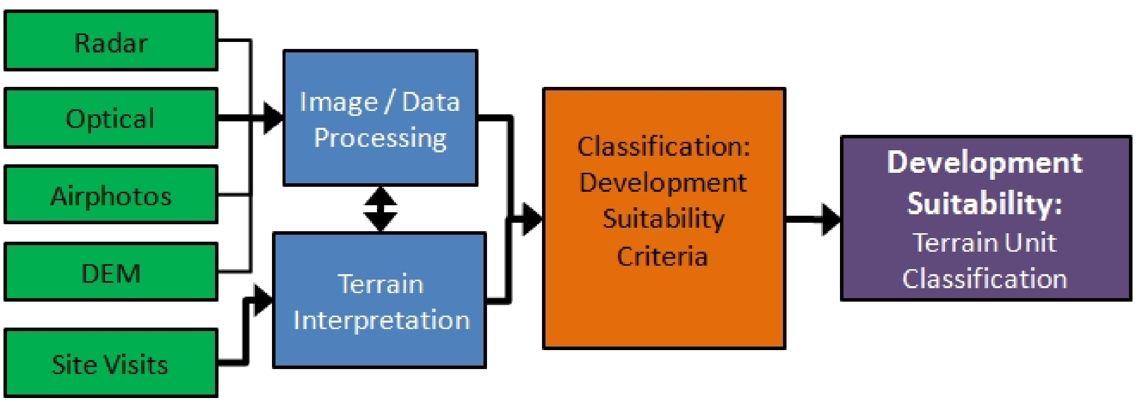

Figure 2 Project Methodology

Figure 2 illustrates a general overview of the project methodology. Each available data set was used to improve determination of terrain suitability. Specific image processing and terrain interpretation techniques (see below) were applied to generate information products required for determining the development suitability of each community. Permafrost engineers worked closely with image processing experts to maximize information extraction from available data. This was a collaborative process with frequent interaction between remote sensing data analysts (3vG) and engineering interpretation personnel (BGC). The following sections describe the methodology applied during the project.

2.1 DATA SOURCES

Several data inputs were utilized to generate suitability maps over the Nunavut communities. This section provides an overview of each type of input data source, and discusses its strengths and limitations pertaining to land suitability assessment.

2.1.1 RADARSAT-2

New acquisitions were planned over each site, supplemented by available archive data. Figure 3 illustrates the data acquisition plan. Significant satellite acquisition conflicts with the Canadian Ice Service (CIS) started mid-October 2010, which resulted in fewer and delayed (winter) image acquisitions for most communities. By coordinating the acquisition plan with the CIS, at least one image pair was acquired over each community.

Community	Beam Mode	Archive		September	October		November		December
Cambridge Bay	SLA16 A	21-Jul-10	14-Aug-10	7-Sep-10	1-Oct-10				
	U25 A			10-Sep-10	4-Oct-10	28-Oct-10			
Chesterfield Inlet	SLA22 D			11-Sep-10	5-Oct-10	29-Oct-10	22-Nov-10		
Rankin Inlet	SLA15 D	22-May-09		14-Sep-10		8-Oct-10	1-Nov-10	25-Nov-10	
	SLA7 A						5-Nov-10	29-Nov-10	
Baker Lake	U79 A			11-Sep-10	5-Oct-10	29-Oct-10			
Hall Beach	SLA25 D	9-Jul-10	2-Aug-10	19-Sep-10					
Sanikiluaq	SLA21 A			19-Sep-10		13-Oct-10		6-Nov-10	
Gjoa Haven	U15 D			20-Sep-10		14-Oct-10		7-Nov-10	
	U18 D				21-Oct-10		14-Nov-10		8-Dec-10
Coral Harbour	U26 D			19-Sep-10		13-Oct-10		6-Nov-10	
Kugaaruk	U23 A			18-Sep-10		12-Oct-10		5-Nov-10	
Taloyoak	SLA14 A			18-Sep-10		12-Oct-10		5-Nov-10	
Repulse Bay	U18 D			25-Sep-10		19-Oct-10		12-Nov-10	
Cape Dorset	U21 D	11 Archived		30-Sep-10		24-Oct-10		17-Nov-10	
Kimmirut	SLA3 D			20-Sep-10		14-Oct-10		7-Nov-10	
	SLA26 D				8-Oct-10		1-Nov-10	25-Nov-10	
	SLA76 A						5-Nov-10	29-Nov-10	
Pond Inlet	SLA21 D			19-Sep-10		13-Oct-10	6-Nov-10	30-Nov-10	
	SLA71 A	16-May-09							

Received	Archived	Programmed	Conflict	Not Acquired

Figure 3 RADARSAT-2 Data Acquisition Plan

RADARSAT-2 data were used for characterizing ground displacement, coastal and water body delineation, and land classification. Data were acquired using RADARSAT-2's Ultra-Fine (3 m resolution) and Spotlight (1.6 m resolution) beam modes to aid land suitability analysis with high spatial detail. The majority of images were winter acquisitions exhibiting significant surface change due to snowfall and gradual freezing of lakes/oceans. Figure 4 illustrates the difference between a summer and winter Spotlight image over Taloyoak. Summer images are much better suited for classification/segmentation of surface features and measurement of ground movement because land characteristics are better preserved between consecutive acquisitions. For instance, relatively superior displacement data and land cover classes were generated over Cambridge Bay due to better timing of image acquisitions.

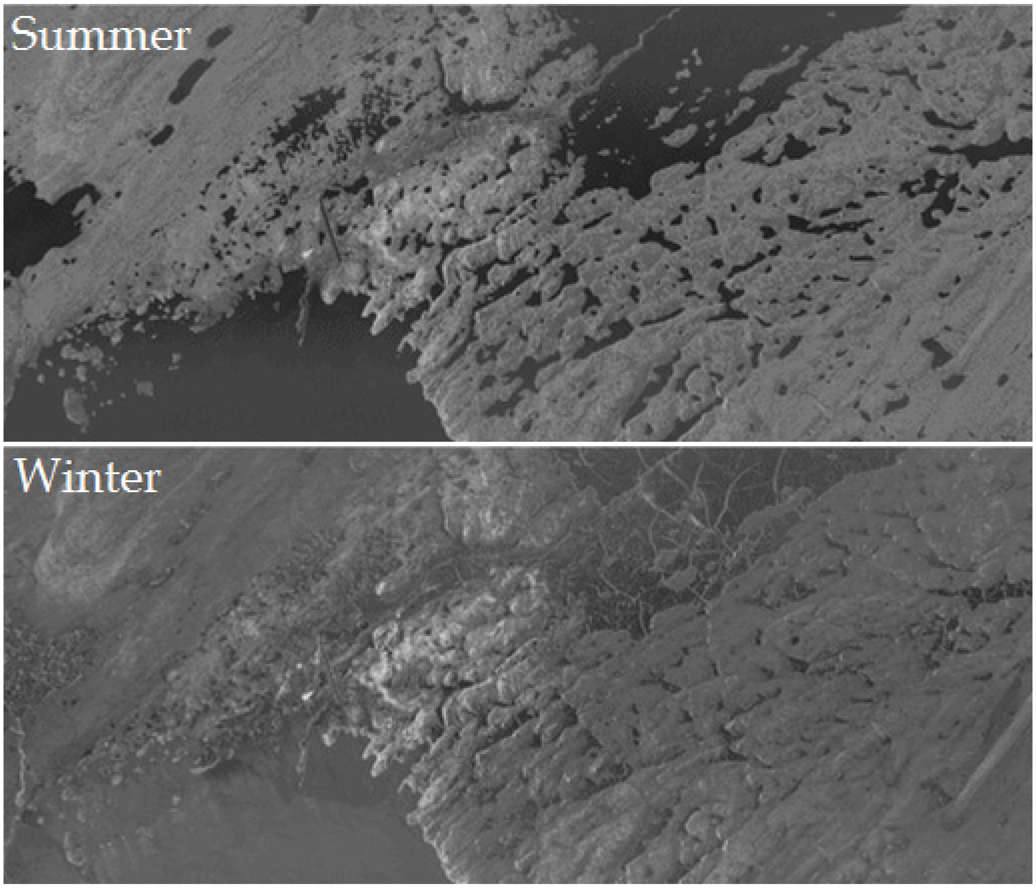

Figure 4 RADARSAT-2 Images over Taloyoak

Another limitation is the relatively few image acquisitions over each site, which reduces the measurement accuracy of ground movement. Cape Dorset is the only community with appreciable data volume enabling accurate long-term displacement mapping. This issue is discussed at length in Sections 2.2.3 and 6.3.

2.1.2 Elevation

An external Digital Elevation Model (DEM) is an important data input for each community for the following reasons:

- it permits delineation of oceans and other water bodies from land;
- slope and aspect can be computed, aiding displacement interpretation and suitability analysis; and
- known topography can be removed from ground movement maps, thereby improving accuracy.

We investigated all available external elevation data over the Nunavut communities. CDED data were used for all communities except for Sanikiluaq, where SRTM was available and used due to its superior vertical accuracy. Table 1 summarizes the characteristics of each DEM source, followed by more detailed analysis and cross-comparison.

Table 1 Available Elevation Data Sources

DEM Source	Posting	Coverage	Notes
Canadian Digital Elevation Data (CDED)[1]	0.75 arc seconds (about 22 m)	Canada	▪ Numerous jump discontinuities between adjacent map sheets ▪ Acceptable vertical accuracy
Shuttle Radar Topography Mission (SRTM)[2]	3 arc seconds (about 90 m)	56°S to 60°N	▪ Excellent vertical accuracy ▪ Coarse resolution ▪ Available only over Sanikiluaq
Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)[3]	30 m	83°S to 83°N	▪ True resolution is much lower than 30 m ▪ Serious artifacts are present
Government of Nunavut (GN)	Variable (30 m to 100 m)	Local, does not cover entire sites	▪ Variable resolution and coverage ▪ Limited value

GN Elevation Data

The elevation data provided by the GN were evaluated against CDED. GN DEMs were received as point clouds or contours, which are not directly useable for land suitability analysis. Hence, we gridded these inputs using a superior interpolation algorithm in order to generate a DEM with regular posting. Figure 5 illustrates the raw and gridded DEM over Cape Dorset. The posting is variable, varying between 30 m and 100 m, with a mean posting of 37 m.

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[1] http://www.geobase.ca
[2] http://srtm.csi.cgiar.org
[3] https://wist.echo.nasa.gov

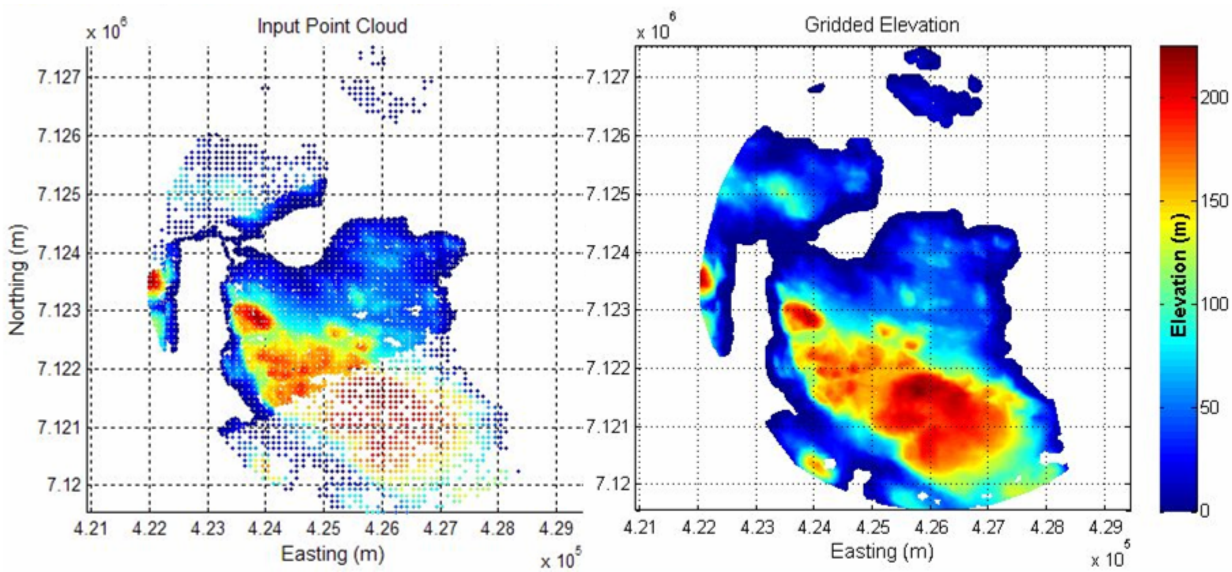


Figure 5 Raw and Gridded GN Elevation Data over Cape Dorset

CDED data were chosen over GN Elevation data due to better AOI coverage, overall resolution, and hydrography including lake flatness and shoreline delineation. Figure 6 illustrates the gridded GN DEM against CDED over Cape Dorset.

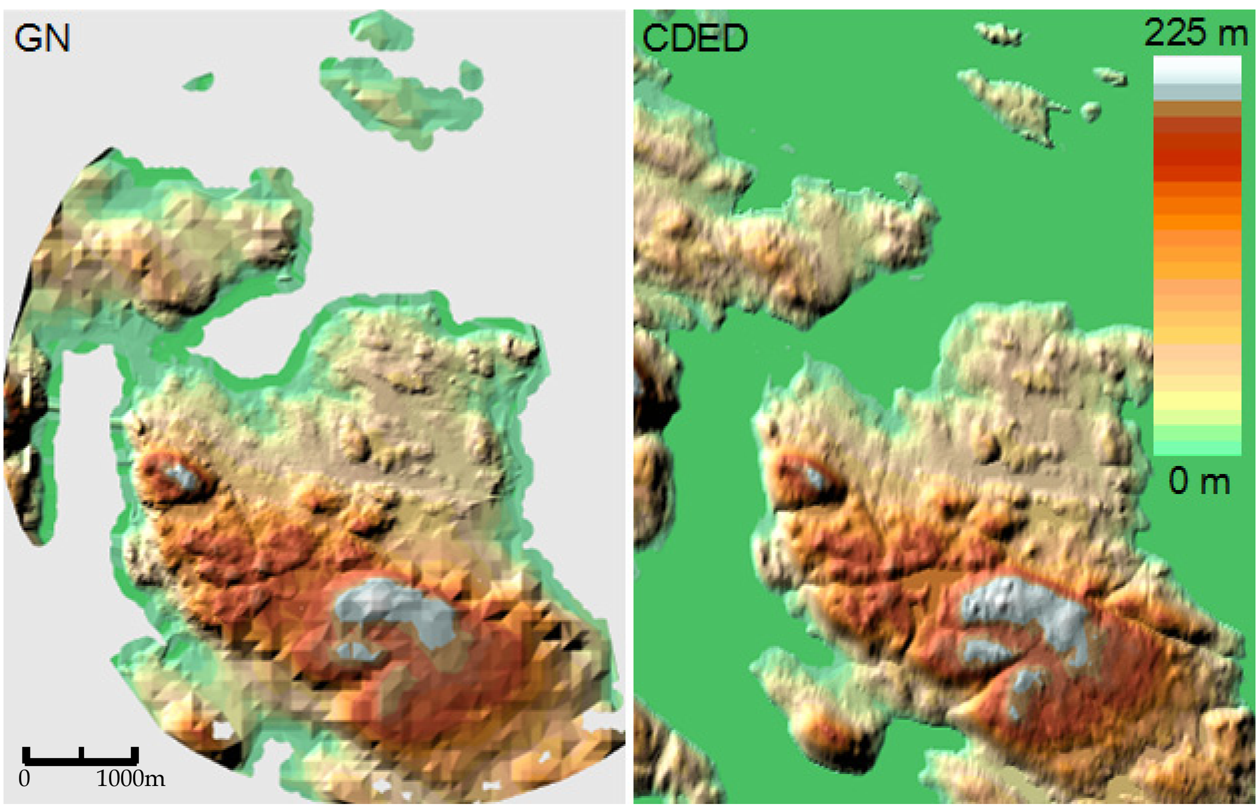


Figure 6 GN DEM vs. CDED over Cape Dorset

Comparison among CDED, SRTM, and ASTER

Since SRTM is available only over the southernmost community of Sanikiluaq, we compared all external DEM sources over this site. Figure 7 illustrates ASTER, CDED, and SRTM over Sanikiluaq. ASTER stands out as exhibiting the worst overall quality with respect to shoreline demarcation, inland hydrology, conspicuousness of land features, and spikes/wells. CDED and SRTM are comparable, and it wasn't initially clear which one was more suitable. After processing RADARSAT-2 data, however, SRTM was more successful in removing the topographic signal thus generating better displacement maps. Hence, SRTM was chosen for processing Sanikiluaq, and all other communities were processed using CDED.

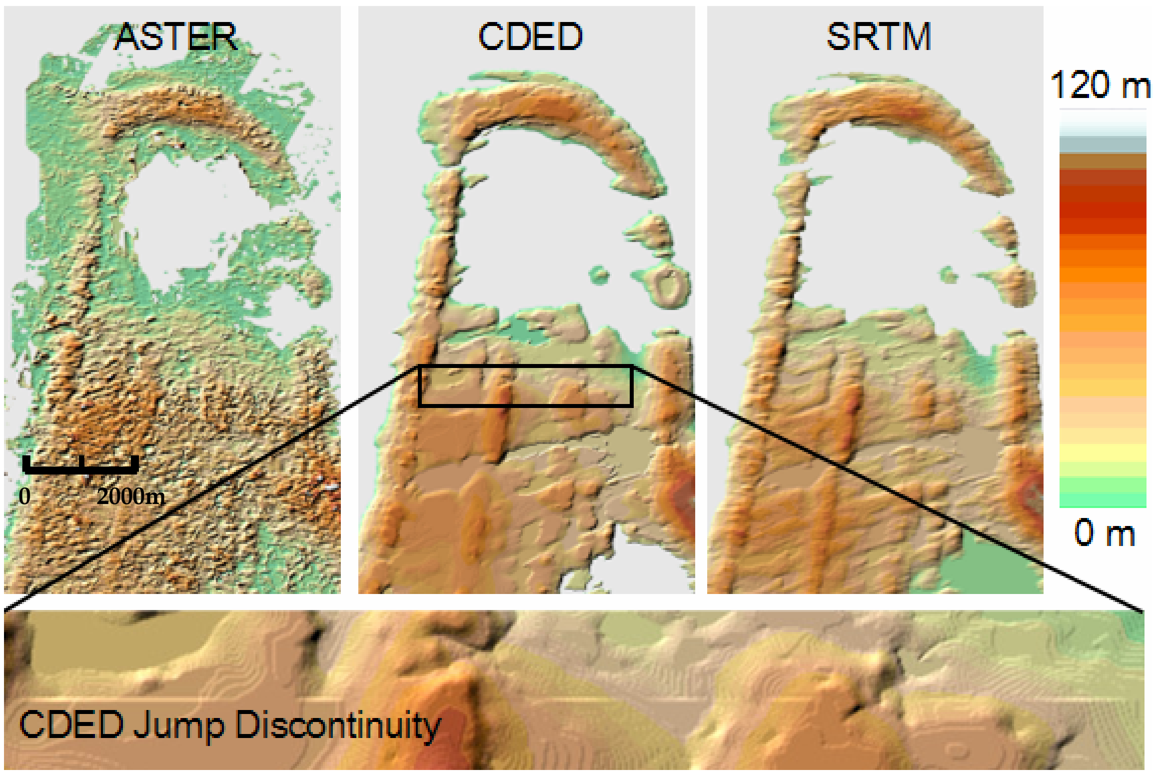


Figure 7 ASTER, CDED, and SRTM over Sanikiluaq

The CDED jump discontinuity seen in Figure 7 is not an isolated anomaly. Several CDED datasets exhibited similar jumps, usually at the boundary of adjacent map sheets. These errors are difficult to remove over land due to the variable elevation relief along the jump discontinuity. However, these errors were manually corrected wherever they were not prohibitively time consuming; for instance, elevation jumps inside water bodies were removed by manually masking and imposing the water level, as shown for Cambridge Bay in Figure 8.

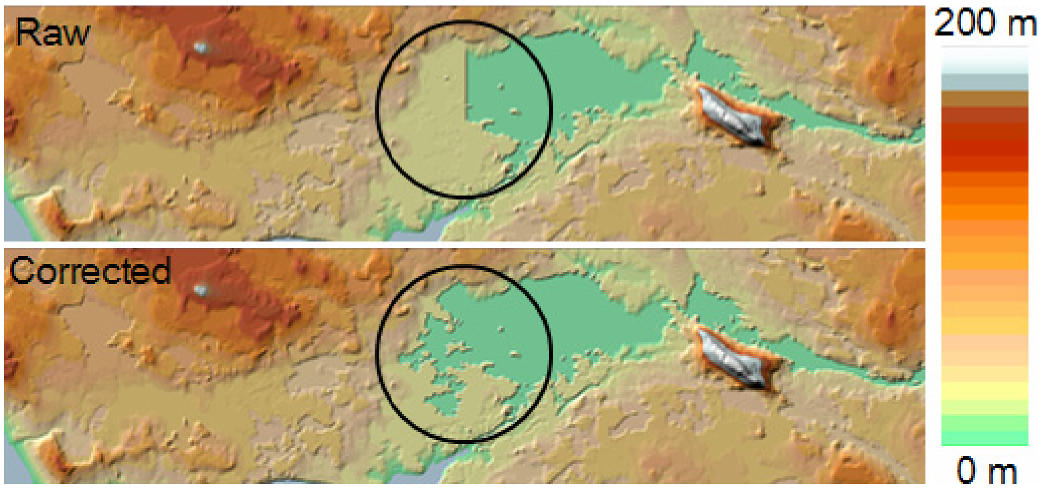


Figure 8 Raw and Corrected CDED over Cambridge Bay

Overall, CDED served as an acceptable external elevation data source over the Nunavut communities.

2.1.3 Optical

Both optical satellite images and air photos were used during the project; however, given the ease of use from the digital format (some air photos were in digital format but coverage was limited) and the more recent acquisitions, priority was given to the optical satellite data.

Optical satellite data exists over each community; however, in most cases the optical data covered only a limited portion of the AOI of each community (Project Area A).

Please refer to the document RFP – *Terrain and Soil Analysis, Nunavut, 2010-69* for details of the air photos and optical data. Appendix A also lists the acquisition dates of the optical data for each community.

Optical images from Google Earth were also used in analysis. High resolution optical data existed at each community, with coverage that often exceeded the optical data provided by the GN.

2.1.4 Vector Data

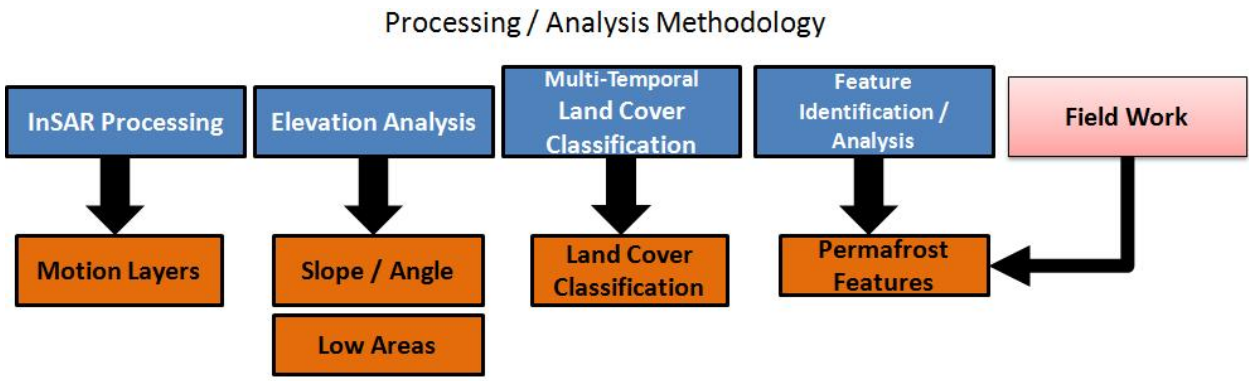
Vector data were provided by the GN that covered the built-up areas of each community as well as additional water body data. Unfortunately, the water body data did not cover all of the AOIs and matched only the coverage of the optical satellite data. Water bodies, transportation (roads, trails, airports) and building footprint data were used to validate layers derived from RADARSAT-2 imagery.

2.1.5 Field visit

Three communities (Cambridge Bay, Gjoa Haven and Taloyoak) were visited between September 27 and October 4, 2010. The site inspections were carried out by 3v Geomatics and BGC to evaluate and inspect features related to radar interpretation as well as identification of permafrost features for the geotechnical assessment. The main objective was the characterisation of the subsurface conditions. A detailed report of this site investigation is presented under a separate cover (Reference 2010 – 69 – Site Visits) and is attached as separate document.

2.2 PROCESSING / ANALYSIS

This section provides an overview of the technical methodology pertaining to the generation of intermediate outputs, as well as the final development of suitability maps.



2.2.1 Data pre-processing

All RADARSAT-2 data was co-registered to match the optical satellite data and vector information provided by the GN.

2.2.2 Elevation Analysis

The slope and aspect are an important intermediate output; they are useful for interpreting the direction of ground movements, and for suitability assessment based on steepness and directionality of a slope. For instance, south facing steep slopes are exposed to more solar radiation than north facing slopes. This may result in warmer ground conditions and increased likelihood for ground movements and degradation. Therefore such slopes are likely less suitable for development than other areas. The local slope and aspect was determined over each community using the external DEM sources described in Section 2.1.2. Figure 9 illustrates these products over Kimmirut.

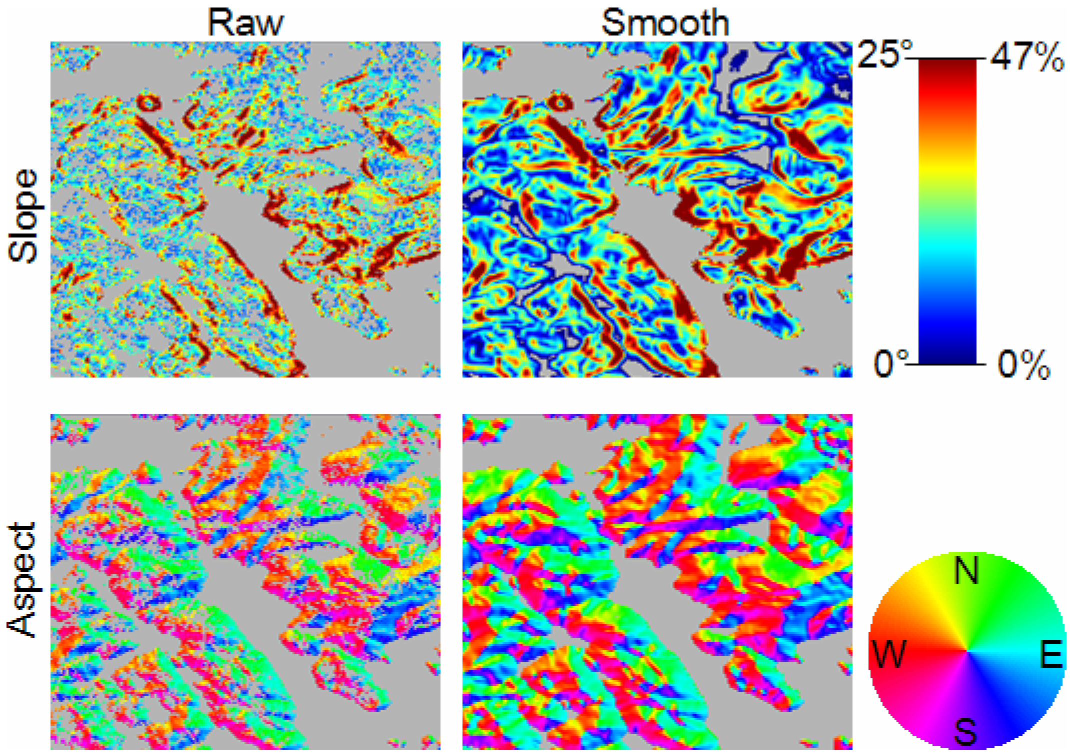


Figure 9 Slope and Aspect over Kimmirut

The slope and aspect generated initially had large gaps due to noise in the source DEM and the generally flat topography. This created problems for the suitability analysis because of intermittent regions with no data. Hence, the slope and aspect were re-computed after smoothing the source DEM. The smoothed slope and aspect are also illustrated in Figure 9.

Elevation data were also processed for each community to identify local low points and depressions. Each point was compared with the surrounding area within a radius of 250 m to determine whether it was more likely to collect water and accumulate sediments, hence provide conditions where ice-rich ground may be present. Massive, segregated ice lenses cannot be identified with such a low point analysis because those areas would show as high points in the area. But it was decided that the rugged bedrock topography, which was identified for most communities, allows for this criterion to identify potential ice-rich conditions.

2.2.3 InSAR Processing

InSAR (Interferometric Synthetic Aperture Radar) is a remote sensing technique that uses two or more overlapping radar images to map the elevation or displacement of the Earth's surface. The accuracy of this technique scales with the volume of available data, and also depends upon site characteristics such as precipitation, land cover, soil moisture, and even atmospheric activity. As a rule of thumb, InSAR can deliver centimetre accuracy with a pair of images, scaling gradually to millimetre accuracy after about 15 scenes have been acquired. Reconnaissance of previously unknown ground displacement is also difficult with 2-3 scenes, but becomes possible after about 5 scenes have been acquired. For this project, we applied InSAR to study the ground movement over each community. The aforementioned limitations were applicable to all communities except for Cape Dorset, where a "stack" of 14 images acquired over 18 months was available. Figure 10 illustrates the InSAR processing chain applied to Nunavut communities, followed by a discussion of the key steps.

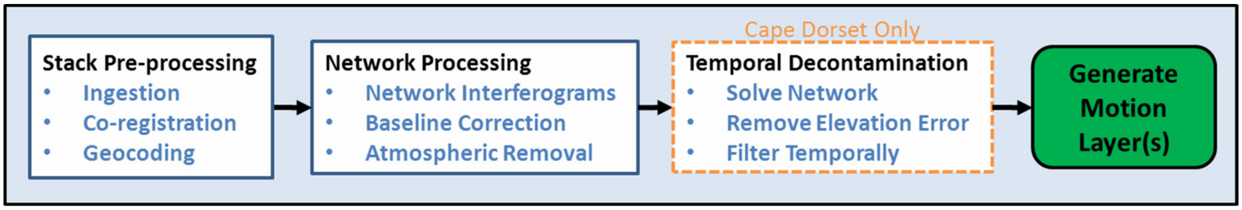


Figure 10 InSAR Processing Chain

Stack Pre-processing

Overlapping images acquired with identical satellite beam modes and near-identical viewing geometry form a "stack" of data. Each stack was imported into the image processing environment, and all scenes in a given stack were exactly matched (or *co-registered*) to a chosen reference scene. Each stack was referenced to an external DEM, enabling georeferencing of all radar outputs. The georeferencing was based on satellite orbits, supplemented by data-based matching in communities with some elevation relief and summer images. A first order shift was then applied to minimize offsets with respect to GN Optical imagery and vector data. Figure 11 illustrates an original and georeferenced image over Hall Beach. The georeferenced image is horizontally flipped and slightly rotated to account for the flight path and look direction of the satellite.

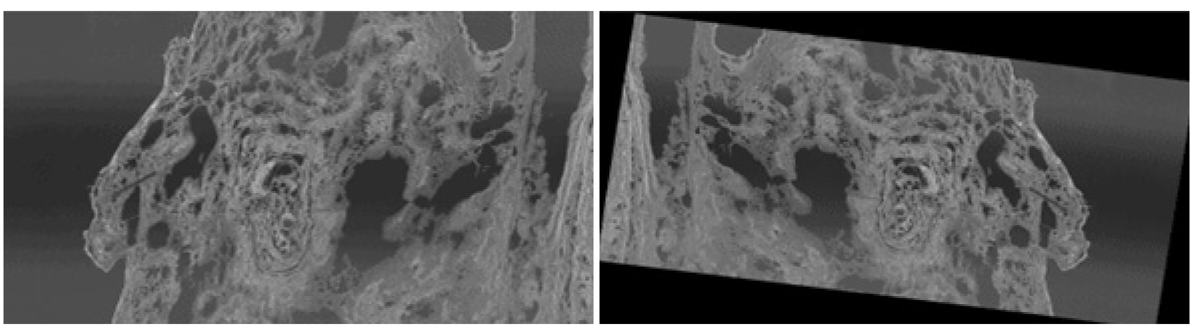


Figure 11 Hall Beach image: Original (left) and Georeferenced (right)

Network Processing

For each stack, all combinations of image pairs were differenced to generate a network of interference images, known as *interferograms*. The satellite eye-distance, called the *baseline*, was corrected by globally minimizing the colour variations in each interferogram. Thereafter, long-scale filtering was applied to model and remove the atmospheric signal. As a whole, the network processing step minimizes the large-scale colour variations in each interferogram so that the displacement signal becomes more prominent for the ensuing processing steps; this is illustrated for Cambridge Bay in Figure 12. The colour variations indicate phase change caused due to contaminants as well as displacement. The network processing accentuates the displacement signal while suppressing the contaminants.

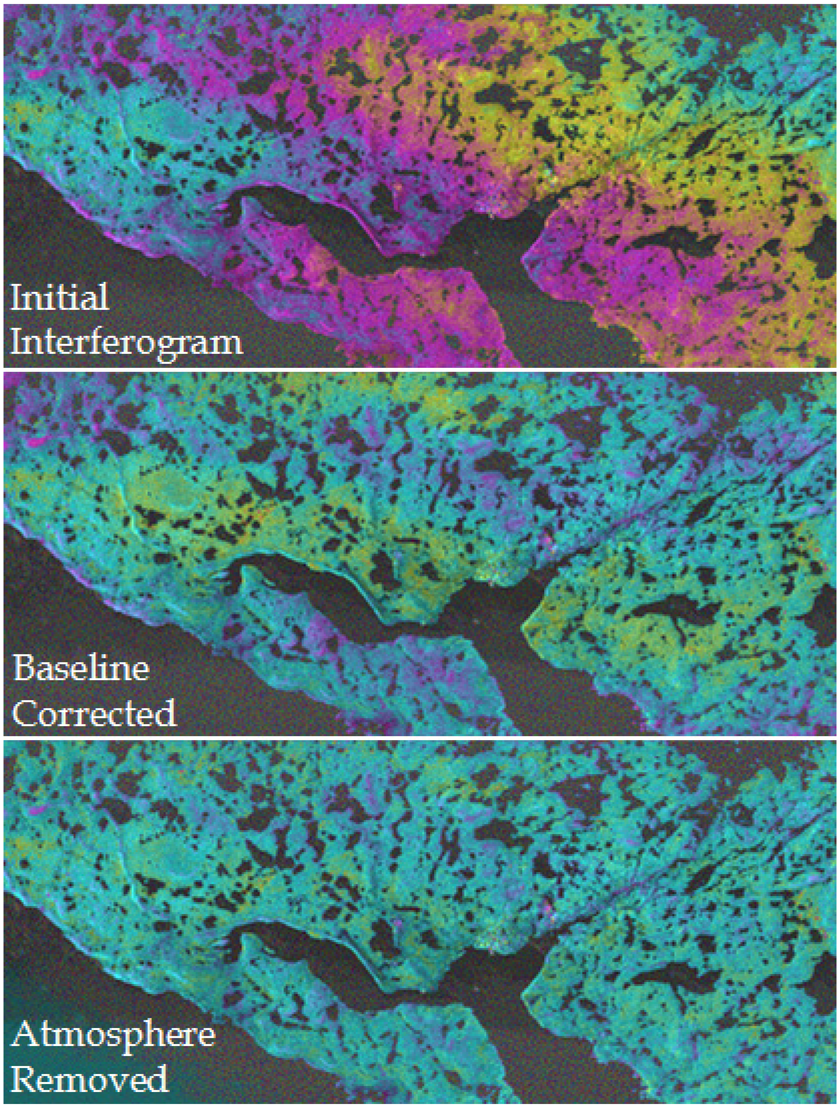


Figure 12 Network Processing for minimizing colour variations at Cambridge Bay

Temporal Decontamination

Temporal analysis is possible once a stack has more than 2 scenes, but adds appreciable value only for stacks containing at least 10 scenes. Hence, we were only able to apply this to the Cape Dorset dataset comprising 14 images. The network of interferograms was optimally solved to generate a cumulative de-noised interferogram for each acquisition date. Elevation error was modeled and removed by examining the temporal distribution of baselines against the signal history at each pixel. Finally, temporal filtering was applied to segregate motion from other contaminating signals (residual height error, short scale atmosphere, soil moisture) that do not evolve smoothly over time. The improvements yielded through temporal decontamination over Cape Dorset are further explored in Section 6.3.

Motion Layer(s) Generation

The final step is to generate one or more motion layers based on the network of interferograms. All communities except for Cape Dorset contained only a few interferograms that were weighted based on data quality and fused to generate a cumulative motion layer. Every stable pixel from each interferogram was factored into the motion layer. Finally, a noise floor was applied to remove contaminating signals that were masquerading as displacement. The noise floor was discretionally determined by observing local atmospheric characteristics, and comparing potential motion clusters against features in amplitude images. Furthermore, small motion clusters were culled based on an empirical threshold. Figure 13 illustrates the above-described evolution of the motion layer for an image subset over Cambridge Bay. A time series of motion layers was generated over Cape Dorset, as discussed in detail in Section 6.3. All motion measurements represent changes in radar line-of-sight (LOS). LOS measures changes in position from the satellite to the ground target. Negative motion indicates that the target moved away from the satellite and positive motion indicates movement towards the satellite.

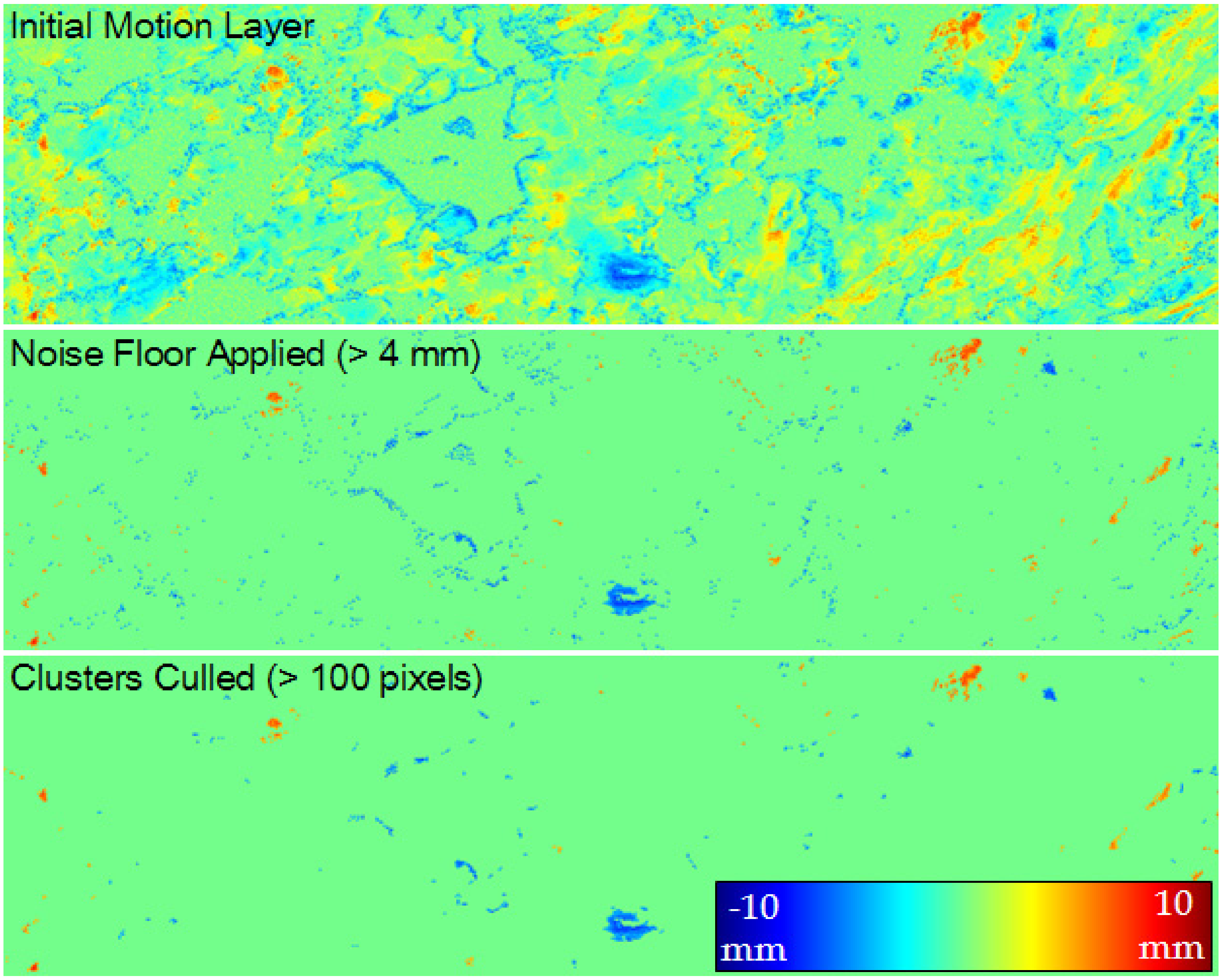


Figure 13 Motion (Line-of-sight) Layer Generation over Cambridge Bay

2.3 MULTI-TEMPORAL LAND CLASSIFICATION

Supervised classification techniques were applied to RADARSAT-2 amplitude, optical images, and coherence imagery to extract land cover types. Coherence images indicate the amount of noise present in an interferogram, which can be used to deduce attributes such as land cover and moisture. In supervised classification, the images are classified by manually selecting training samples of specific land cover types throughout the image. Using the training samples, a statistical analysis is then applied to separate each pixel into the most likely class. Prior to classification, a median filter (5x5) is applied to each RADARSAT-2 image to minimize the effects of radar noise (speckle).

Figure 14 Multi-temporal RADARSAT-2 Data at Cape Dorset

Figure 14 demonstrates changes identified with multi-temporal RADARSAT-2 data at Cape Dorset. 3 images are used from September 2009, October 2010 and December 2010. Temporal changes can be identified from colour discrepancies. For example, the red areas show ice forming around the coast in October and the blue areas show where ice has covered lakes and oceans completely in December. Such temporal analysis is used to identify different classes at each community.

Initially up to 12 separate classes are generated for land and water types. These classes are then amalgamated into the following main classes:

a. Water bodies

b. Low vegetation covered areas

c. Exposed, bare soil

d. Exposed rocks/bedrock

e. Wet Areas

f. Built-up/Urban areas

Filtering is then applied to the classification to eliminate isolated pixels. Manually editing is used to correct identified misclassifications.

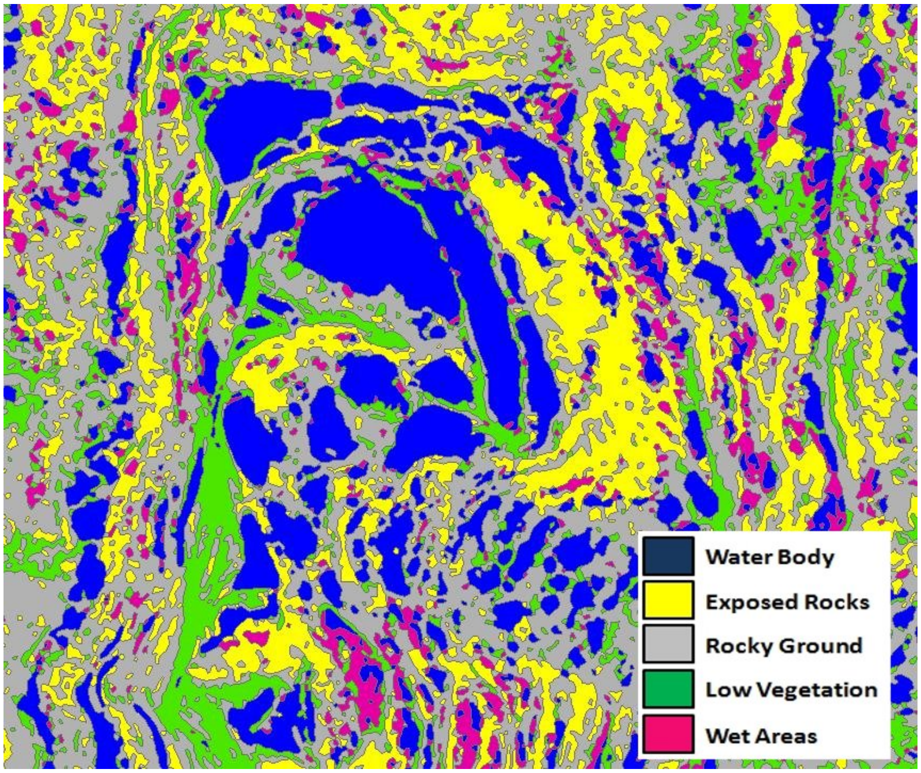


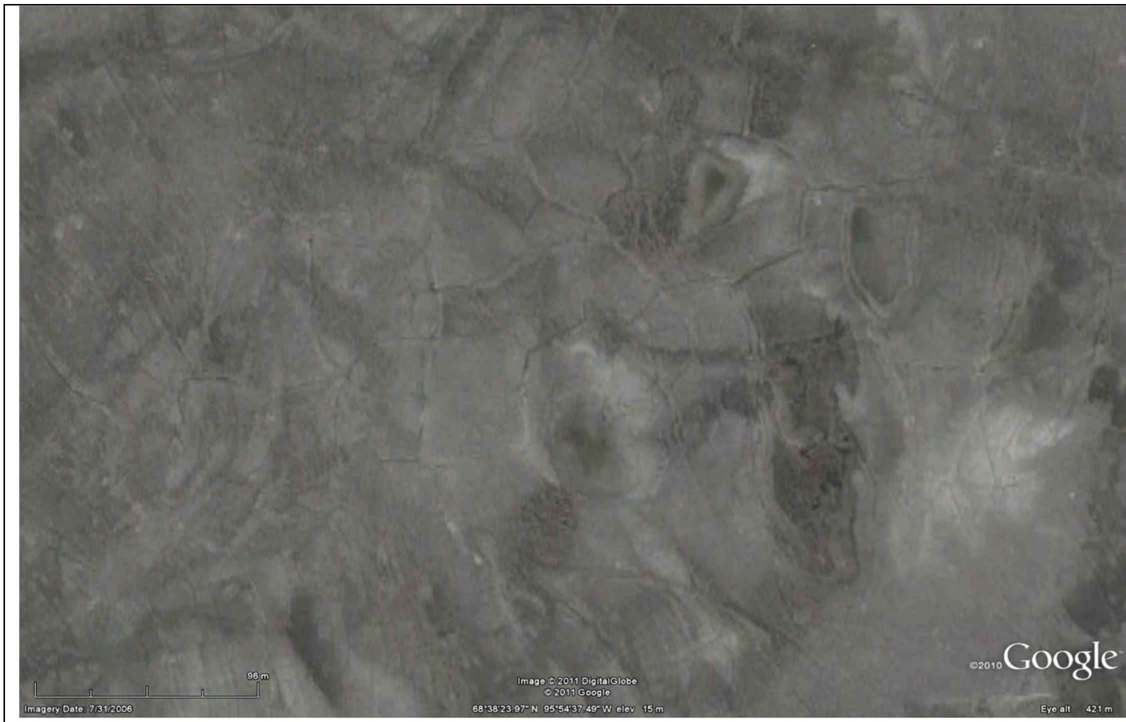
Figure 15 Classification Results

Figure 15 shows a sample of classification results from Hall Beach.

2.4 PERMAFROST IDENTIFICATION

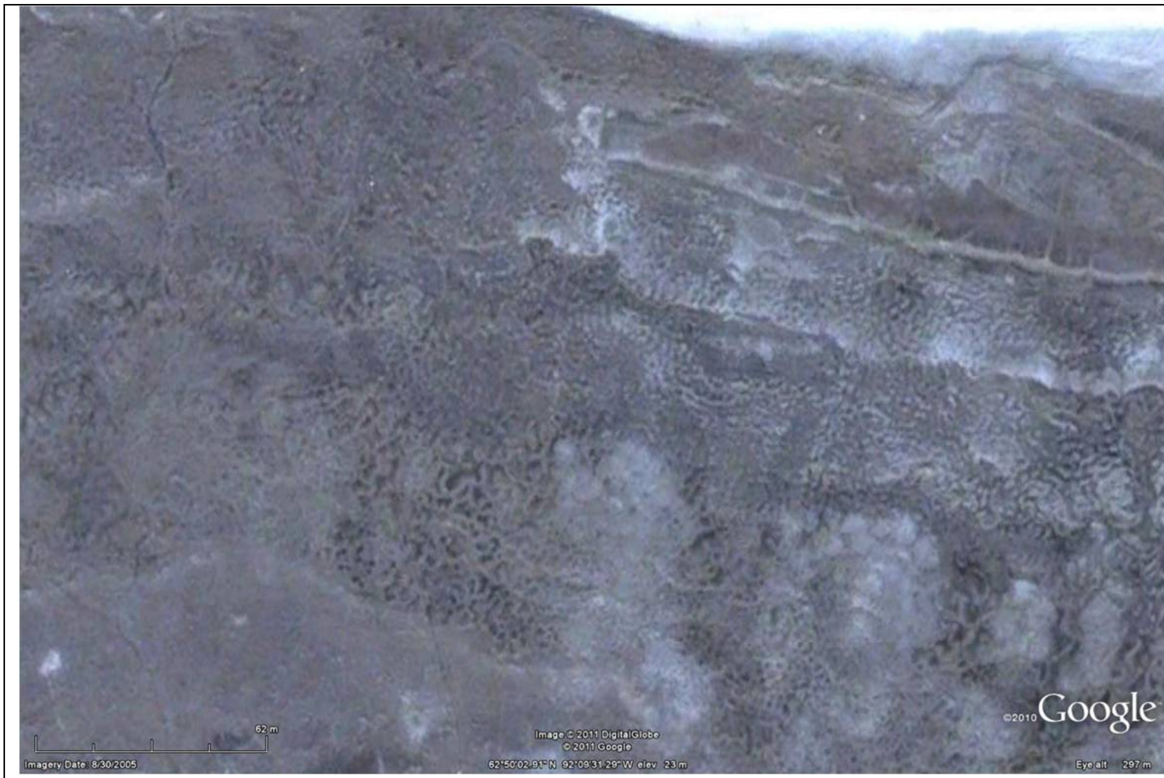
Each Community was visually inspected using optical images and compared to the standard classification described above. The goal of these inspections was to identify potential ice-rich ground conditions, which often result in typical surface landforms. However, potential massive segregated ice, which could also form in bedrock, may not express any identifiable surface forms and may therefore not be recognised, also due to the limited resolution of the images. Typical landforms are summarized in Table 2.

Table 2. Examples of surface expressions that may be identifiers for ground ice.

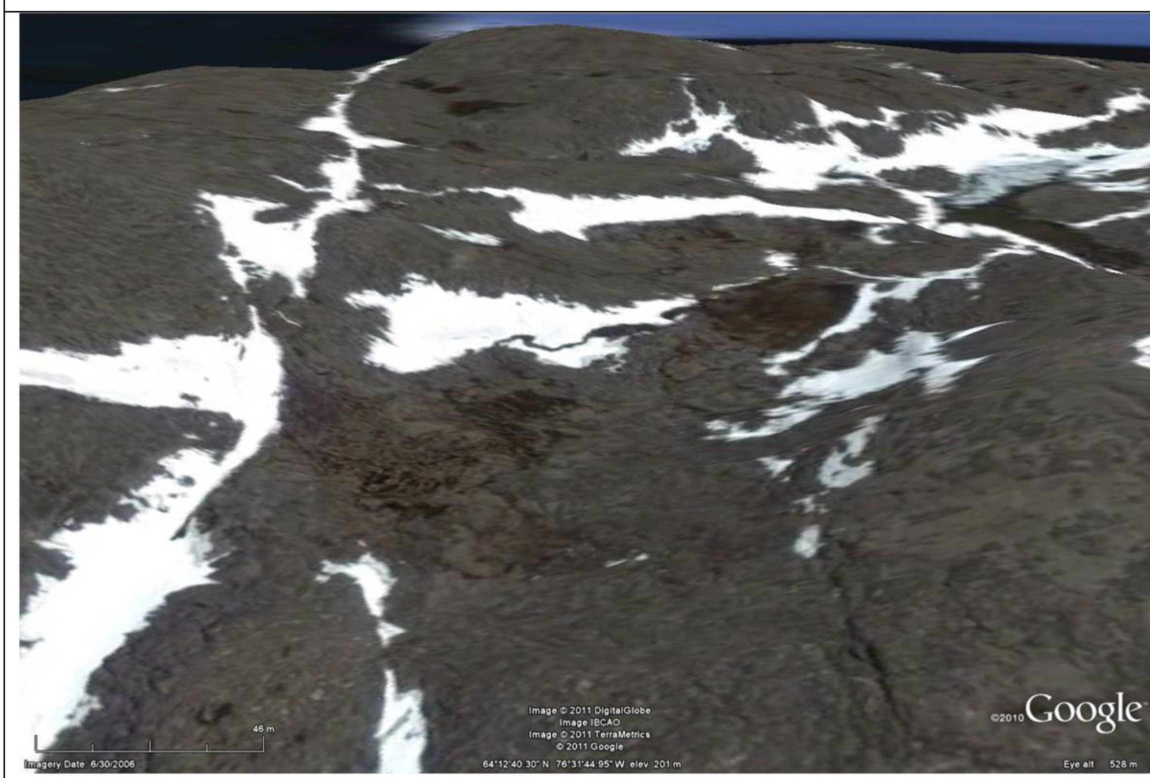


Ice Wedge Polygons at Gjoa Haven.

Thermokarst lakes at Gjoa Haven



Patterned ground (hummock) at Rankin Inlet



Sediments/patterned ground in bedrock trough at Cape Dorset.

Pattern ground and gullying at Sanikiluaq.

2.5 SUITABILITY FOR DEVELOPMENT

The suitability for development should mainly be based on the ground ice conditions and how those may change with time. It is likely that massive ground ice degradation and active layer thickening will occur in the future, which will result in changed foundation conditions. In addition, sea level rise and coastal erosion may affect areas close to the sea. The methodology was therefore developed to estimate and identify areas that are potentially underlain by ice rich ground and these should therefore not be used for any future development. It is also more likely that ground ice formed in lowlands and is present around thermokarst features. Aspect and slopes may also play a role because of the change in solar radiation as well as potential for gravitationally driven mass movements.

Because surface deformations in permafrost areas are often seasonally driven, some ground deformation may not have been identified because of the winter data available, i.e. the time span over which the images were taken.

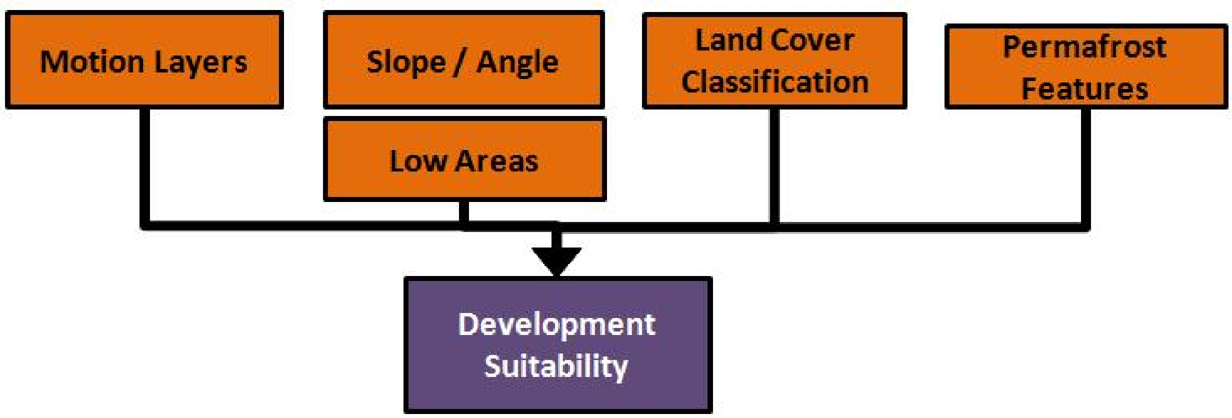


Figure 16 Inputs to Development Suitability

Figure 16 shows the key inputs into generating the Development Suitability Maps:

- Motion layers
- Slope/Aspect - Low Areas
- Land Cover Classification
- Permafrost Features

The following classes and determining criteria were established through discussions with the GN and were used in developing the Development Suitability Maps:

- **No Data**: In some communities the RADARSAT-2 or optical data did not cover the entire AOI and no conclusions could be made from suitability indicators.

- **Suitable for development**: Area that is thought to be stable and available data has indicated little or no evidence of ice-rich and changing permafrost conditions.
    - Exposed Rock, bare soil, low vegetation
    - Slope < 4%
    - Aspect – No South Facing
- **Possibly suitable for development**: The area is possibly stable for development; Ground conditions have limited indicators of changing permafrost conditions. In some cases, due to the lack of quality remote sensing data, the presence of permafrost could not be ruled out.
    - Exposed Rock, bare soil, low vegetation
    - Slope < 4%
    - Aspect– No South Facing
- **Marginally suitable for development**: All data indicates that some ground ice is present and the area is therefore only marginally suitable for future development.
    - Low vegetation
    - Slope 4 - 10 degrees
    - Include South Facing
- **Unsuitable for development**: Rugged terrain, evidence of ground ice or subsidence, and surface water identified in the area.
    - Wet areas
    - Within 25 m of displacement
    - Within 30 m of water body
    - Slopes > 10%
- **Built-up**: Urban areas and airports were manually digitized from optical satellite images.

Additional Suitability Criteria included:

- Low areas were also identified from the elevation (DEM) data within each AOI and their suitability reduced because of the likelihood that ground ice may have formed by segregation where water accumulated. Low areas that were Suitable were reduced to

- The Unsuitable buffer around water bodies was reduced to 5 m in areas of bedrock.
- In areas that were predominantly bedrock or exposed rock, the suitability of low vegetation areas was reduced.
- Areas that were smaller than 1.2 ha were eliminated converting them to the dominant surrounding class, as determined by the longest surrounding border.

3.0 PROJECT SITES

This section provides processing notes and site-specific nuances that were encountered during analysis of each of the 14 Nunavut communities.

3.1 CAMBRIDGE BAY

Displacement Analysis

Two Ultra-Fine Images were acquired over Cambridge Bay in October, but the resulting interferogram was very noisy due to significant land cover changes between the acquisitions. Hence, only the Spotlight stack comprising 4 summer scenes was used for displacement analysis. Six interferograms were generated and exhibited excellent quality. Network Processing (Section 2.2.3) was applied, and each layer was weighted to generate an integrated motion layer representing the cumulative displacement during the dataset time span. A 4 mm displacement noise floor was applied and motion clusters smaller than 100 pixels in size were culled, as illustrated earlier in Figure 13.

Suitability Analysis

The area surrounding Cambridge Bay has very little topography and is characterised by low Tundra vegetation and several ponds of different sizes. Bedrock outcrops are sparse leaving most areas with overburden of variable thicknesses. Patterned ground with ice-wedge polygons of different sizes as well as thermokarst features exist in the area indicating ice-rich ground conditions. Because of the low elevation and flat topography, high salinity is expected in the frozen ground for the whole region.

This heterogeneity of bedrock and ice-rich ground resulted in very limited areas classified as suitable for development, and the majority of the study area was identified as non-suitable. The area is generally considered to contain significant amounts of ground ice. Expected rise in the sea level may also have to be considered in future development planning.

3.2 CHESTERFIELD INLET

Displacement Analysis

Three Spotlight images were acquired over Chesterfield Inlet, and 3 interferograms were generated by differencing each image with respect to every other image. The interferograms exhibited medium quality, and were weighted and integrated to generate a single motion layer. By comparing against features in amplitude images, a potential motion signature was visually identified in this dataset. Hence, a lower noise floor (4 mm) and small motion cluster threshold (50 pixels) was applied in order to retain this motion signature.

Processing Notes / Known Issues

- DEM quality was very poor; identifying lower areas where collection of water and moisture are more likely was limited by the quality of the elevation data.

- Optical Quickbird imagery covered 100% of AOI and provided additional information to the RADARSAT-2 data
- Images were acquired in winter only (October – November) and much of the ground was expected to be covered with snow and frozen
- The RADARSAT-2 image acquired on October 28 had some processing/data quality issues:

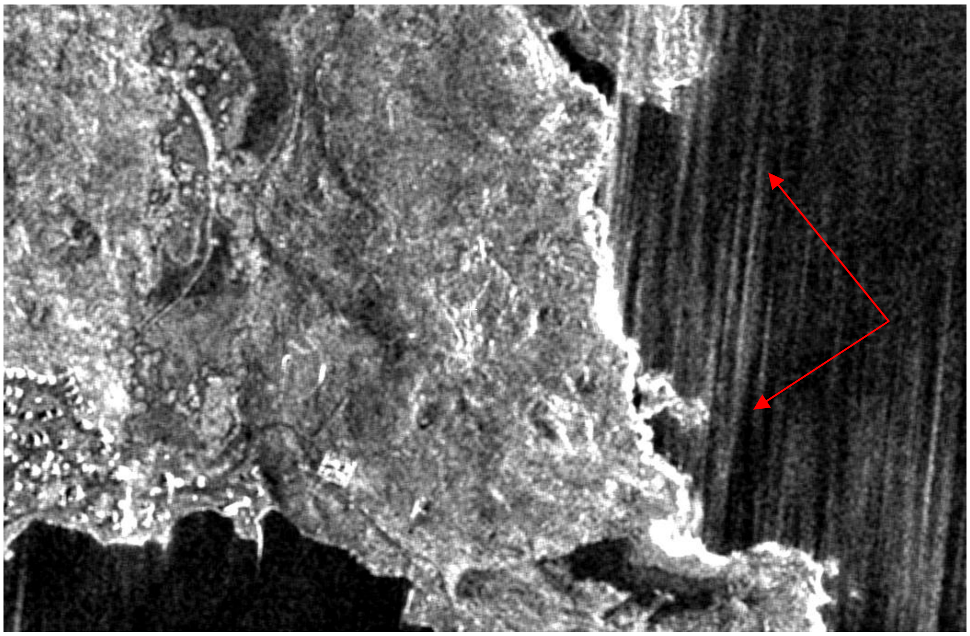


Figure 17 Chesterfield Inlet: Bright targets were saturated, creating linear features.

The image shown in Figure 17 could not be corrected without requesting CSA to reprocess the original data.

Suitability Analysis

The area around the community of Chesterfield Inlet has very little topography. Only at the south western edge of the area of interest some elevations ~30 m above sea level are noted. Overburden thicknesses are variable throughout the study area. The southern portions and coastal areas generally seem to have thin overburden and exposed bedrock, therefore ice-rich ground is likely limited. The areas in and around the numerous ponds are where the greatest thickness of overburden are to be expected, and therefore presence of ice-rich materials unsuitable for development. Approximately 1 km south and southwest of the airstrip, a large area of pattern ground (ice-wedge polygons) is present. This area would be high in ice content and unsuitable for development. Massive ice can also form in bedrock by segregation and therefore the existence of ground ice cannot be ruled out anywhere in the study area. Nevertheless, the bedrock outcrops seem to be suited for future developments, in particular if slightly elevated. The frozen ground is also likely to have high salinity, which affects the freezing point and strength characteristics of the soil, causing it to be more susceptible to degradation.

3.3 RANKIN INLET

Displacement Analysis

Two separate Spotlight (SL) stacks were acquired over Rankin Inlet: SL-15 comprising 3 scenes, and SL-7 comprising 2 scenes. The former stack contained a scene from May 2009 that could not be co-registered with the other two images from winter of 2010. Moreover, the interferogram derived from the 2010 winter images had very high noise due to substantial land cover changes occurring during the 48 days separating the two acquisitions. Hence, displacement analysis was only possible with the other SL-7 stack acquired in November 2010. A single interferogram was generated with the two scenes comprising this stack; it exhibited high noise due to snowfall and freezing that occurred between acquisitions. This single interferogram was converted into a low-quality motion layer, and no motion was visually discernable above noisy blotches throughout the image. Two motion layers were generated with noise floors of 8 mm and 10 mm and cluster removal threshold of 100 pixels and 50 pixels respectively. Displacement analysis suffered due to lack of suitable data over this community.

Processing Notes / Known Issues

- Most imagery over Rankin Inlet was acquired during the winter, with significant snow cover
- Snow cover made classification of different ground cover types difficult particularly with rockier areas and vegetated areas

Suitability Analysis

The community of Rankin Inlet is located in an area with only little topography. A gentle sloping trend, of less than 0.5 degrees on average, exists from the higher elevations in the northwest towards the sea in the south east. There are two bedrock ridges that are aligned in the same direction, one located at the southern end of the study area and the other at the air strip. Based on vegetation data, large parts of the study area are likely covered with overburden. In combination with the flat topography, ice-rich ground conditions are likely in the tundra. Large ice-wedge polygons, various other forms of patterned ground and thermokarst features are visible in the optical images available.

Because only winter data are available for the deformation analysis, the dynamics of this landscape, which is expected to exist based on air photo interpretation, could not be captured. Also, the limitation in the DEM hinders the identification of polygons and thermokarst depressions. Therefore, although the majority of the area is classified as “possibly suitable for development”, this may not be necessarily correct. There are several instances in which areas with ice-wedge polygons (as determined by optical imagery in Google Earth) are being classified as “suitable” and “possibly suitable”, whereas they could be “marginally suitable” to “unsuitable”. In most cases, areas of bedrock should be suitable for development, whereas areas with thick, ice-rich overburden should be avoided, particularly where drainage channels, polygons and thermokarst is present. Ice-rich soil conditions, which are very sensitive to thermal disturbance from construction activity or changes in climate, are expected to dominate in the area. It is further expected that due to the low elevation of the study area, that the salinity in the ground ice is high, and therefore possibly more sensitive.

3.4 BAKER LAKE

Displacement Analysis

Baker Lake was imaged by an Ultra-Fine stack comprising one September image and two October images (2010), yielding three interferograms. The interferogram formed using the first two images had high quality, but the other two interferograms had extremely poor quality and were not useable for displacement analysis. The single high-quality interferogram was used to generate a motion layer. A high noise floor (10 mm) and cluster threshold (100 pixels) was applied because of extremely active short scale atmospheric signal, which can only be removed using temporal decontamination (Section 2.2.3). No motion signal standing out above the noise floor was visually identified.

Suitability Analysis

Baker Lake is a community on the western edge of a tidal-influenced lake. The town is located at the water's edge and the local topography rises to over 80 m above sea-level within 2 km from the coast. The landscape is typical Canadian Shield, with bedrock outcrops, numerous lakes and areas of tundra-covered overburden of various thicknesses. From the optical imagery, few signs of thermokarst or polygonal features are noted. Some thermokarst depressions are noted around ponds, where ice-rich conditions are expected. There are, however, extensive surface water drainage features across the entire study area in the form of rills and gullies in and between lakes. An example for ice-wedge polygons can be found in an area, approximately 3 km north east of the air strip. Even though this area was classified as suitable for construction, it is likely less suitable based on the polygons identified.

Areas of bedrock should be suitable for development. Areas covered with overburden may be suitable for development. It would be necessary to plan surface water controls and drainage options on areas of overburden. Coastal development should also take into account the expected climate induced sea-level rise.

3.5 HALL BEACH

Displacement Analysis

Three summer Spotlight images were available over Hall Beach, and two of the three resulting interferograms exhibited superior quality. All high-quality pixels were weighted into an integrated motion layer that showed a lot of signal around lakes, indicating contamination from soil moisture. Although this didn't make a big difference for the terrain suitability analysis (since lake shores aren't conducive for development), it nevertheless demonstrated the signal ambiguity that can result in the absence of temporal decontamination. Two separate motion layers were generated with a noise floor of 5 mm and 8 mm, and a motion cluster removal threshold of 50 pixels and 100 pixels respectively. These two layers were applied in a cascade during the suitability analysis.

Processing Notes / Known Issues

- Summer RADARSAT-2 acquisitions were very high quality.
- DEM quality was very poor and identifying lower areas where collection of water and moisture are more likely was limited to the quality of the elevation data.

Suitability Analysis

The community of Hall Beach is situated in an area with very little topography and generally only a couple of meters above sea level. Optical images indicate numerous ponds, thermokarst gullying (specifically surrounding the ponds) and patterned ground (high-centred, ice wedge polygons, which indicates degrading permafrost) indicating likely widespread ice-rich sediments. In addition, the salinity is likely high in these grounds, which reduces the freezing point and allows the permafrost to degrade faster. However, several bedrock outcrops are also visible making a classification using a generalized methodology very challenging.

The results of the suitability classification around Hall Beach are to be used with care and should only serve as a general guidance. It is likely that areas identified as suitable are found to be unsuitable for development upon in-situ examination and areas classified as unsuitable may in fact be suitable for certain structures.

Generally, it is considered challenging to build new developments in the community of Hall Beach due to the potentially saline and ice-rich grounds at very low elevation. Potential options for development sites are located at the slightly elevated area towards the west of the airstrip, where bedrock structures are clearly visible. Beach areas are less suitable because of the potentially ice-rich ground and expected sea level rise which will result in permafrost degradation and coastline erosion.

3.6 SANIKILUAQ

Displacement Analysis

This community was covered by three Spotlight scenes that were mutually differenced to generate three interferograms with excellent quality. Two parallel processing threads were spawned using CDED and SRTM external elevation data respectively. The topographic signal was more ably removed by SRTM, which was used for the ensuing displacement analysis. Each interferogram was weighted into an integrated motion layer exhibiting continuous spatial coverage over the entire community. Most of the signal observed in the motion layer was visually correlated with topology (not motion) and other features in the amplitude images. Also, soil moisture signal was observed around lake perimeters, and along the coastline to a lesser extent. Two motion layers were generated with 5 mm and 8 mm noise floors, and 100 pixel and 50 pixel motion cluster culling threshold. These layers were incrementally applied during terrain suitability analysis. The high quality in the three interferograms yielded a high-quality integrated motion layer, but very little motion signal remained after the application of the noise floor, indicating a mostly stable land surface during the dataset time span.

Processing Notes / Known Issues

- Elevation data was extremely poor and did not allow for low point analysis

Suitability Analysis

Bedrock dominates the landscape of Sanikiluaq, situated on the northern coast of Flaherty Island in Hudson Bay. The island has very little topography, rising to maximum elevations of ~30 m above sea level. From the optical imagery, extensive sorted and patterned ground is noted everywhere there is overburden, which is expected to be thickest in between ponds. This patterned ground has potential to be ice-rich and therefore unsuitable for development. Thermokarst features are also noted at the edges of some of the ponds. Due to the close proximity to the sea, high salinity is further expected in the frozen ground, which reduces its strength and affects the degradation.

Due to the harsh environment, little vegetation grows on the island. As such, some of the overburden that has been classified as "suitable for development", because the bare soils and gravels may have been misinterpreted as bedrock by the remote sensing. The overburden in the area is generally considered to contain significant amounts of ground ice due to the pervasive occurrence of patterned ground. Areas of bedrock should generally be suitable for development, however massive ice can exist as segregation ice within the joints and faults. Thus, field investigations are warranted before undertaking development on the island. For potential future development along the coast, including the shoreline of the tidal connected lakes and ponds, climate-induced sea level rise should be considered.

3.7 GJOA HAVEN

Displacement Analysis

Two Ultra-Fine (UF) stacks were acquired over Gjoa Haven: UF-15 comprising 2 images, and UF-18 comprising 3 images. The former contained a winter scene from November, and the resulting interferogram had nearly zero quality due to substantial snowfall and freezing between the two acquisitions. Hence the latter UF-18 stack was exclusively used for displacement analysis; it comprised three scenes that were mutually interfered to generate three interferograms with medium quality. The interferograms were weighted and integrated into a motion layer containing some signal that was not correlated with topology (likely motion). Two separate motion layers were generated based on a noise floor of 5 mm and 7 mm, and a motion cluster threshold of 100 pixels and 50 pixels. These layers were incrementally applied during terrain suitability analysis.

Processing Notes / Known Issues

- No bedrock, so 30 m buffer was applied throughout
- Exposed rocks/gravel were present throughout

- Due to the winter acquisitions, wet areas were not easily identified
- Exposed rock/gravel areas were left as suitable while low vegetation areas were reduced to possibly suitable

Suitability Analysis

The community of Gjoa Haven is situated in an area with very little topography and bedrock outcrops. Most areas are covered with small vegetation, i.e. tundra. The optical images show patterned grounds with large polygons, indicating ice wedges, and thermokarst features around the edges of ponds and areas of surface run-off and deep gullies. Ice-rich conditions, with frozen grounds likely containing a high salinity, are expected for the whole region. Therefore, large parts of the area of interest are classified as possible and marginally suitable. Some sections along the shoreline are identified as suitable for development, mainly because of the lack in vegetation, hence gravel or possible bedrock. However, sea level rise may have to be considered if these areas are chosen as potential sites for future developments. The area is generally considered to contain significant amounts of ground ice.

3.8 CORAL HARBOUR

Displacement Analysis

A pair of Ultra-Fine images was acquired over Coral Harbour, yielding a single interferogram exhibiting good quality. The motion layer was based on this lone interferogram, and contained some signal that was clearly correlated with topology (height error). Most of this topographic signal was evicted after applying noise floors of 5 mm and 8mm with motion cluster thresholds of 100 pixels and 50 pixels respectively. The remnant signal was not correlated with topography and could possibly be motion.

Processing Notes / Known Issues

- Exposed rock/gravel areas were left as suitable while low vegetation areas were reduced to possibly suitable

Suitability Analysis

The suitability map of Coral Harbour reflects the heterogeneity in the surface conditions. The area is characterized by numerous surface ponds, creeks and ditches that meander through the flat topography that contains large wetlands. Several thermokarst features and patterned ground is visible, which indicates a dynamic and likely ice-rich permafrost environment. Even though a significant part of the area is classified as suitable for development, the study area lacks any large continuous areas of individual suitability classes. This indicates that the area is likely not as suitable for development as the remote sensing data indicates.

Because of the low, gently seaward dipping topography, there are no large areas of highlands with thin overburden that could be used for future developments. However, small elevated areas of fluted or ridged bedrock outcrops exist in close proximity to the town limits that could be used for individual structures. Also, development along coastal areas should be avoided due to potential rises in sea level from climate warming. Future developments would therefore have to be planned by studying local conditions individually rather than relying on generalized classifications.

3.9 KUGAARUK

Displacement Analysis

Three Ultra-Fine images were available over Kugaaruk, and were mutually interfered to generate 3 interferograms exhibiting medium quality. Network processing was applied, and the layers were weighted to generate an integrated motion layer. Since 3 scenes are not sufficient to apply temporal decontamination, it was difficult to separate motion from contaminants including short-scale atmosphere, height error, and soil moisture. In order to aid the ensuing suitability analysis, two separate motion layers were generated:

- o Low noise floor (5 mm) and high motion cluster threshold (100 pixels)
- o High noise floor (8 mm) and low motion cluster threshold (50 pixels)

These two layers were incrementally used during the terrain suitability analysis.

Processing Notes / Known Issues

- RADARSAT-2 Ultra Fine 25 beam mode data was acquired from September to November 2010. Significant snow cover was present in all but the first image
    - o Snow cover limited information generated from surface roughness which is critical in identifying land cover and soil types
    - o Not all water bodies would have been identified
- DEM quality is limited and identifying lower areas where collection of water and moisture are more likely was limited to the quality of the elevation data

Suitability Analysis

The community of Kugaaruk is situated in an area of low elevation in between elevated bedrock platforms to the north and south. The elevation of the bedrock outcrop, which is more than 200 m higher than the lowlands on the west side of the study area (at the coast line) gently dips towards the east.

Overburden of various thicknesses exists over the majority of the study area. Hummocky and patterned ground, which has the potential for ice-rich conditions, appears to be prevalent in areas of thicker overburden, i.e. those areas in lower elevation, drainage channels and ponds. Numerous thermokarst ponds are present in the north eastern quadrant of the study area, especially along the Kugajuk River (which is likely tidally influenced) and its flood plain. It is expected that the ground ice will have high salinity, which reduces the freezing point and allows the permafrost to degrade faster. The suitability for development in these lowlands is therefore thought to be marginally at best, but to be confirmed in situ.

The irregular bedrock surface results in several local depressions, where water accumulates and small ponds form. However, very little sediments are expected in these ponds, in particular at higher elevations. Hence little ground ice, if any, is expected and these areas may be suitable for development, even though they were classified as unsuitable in the general algorithm because of the presence of water. Bedrock outcrops at lower elevations are generally less suited for development compared to the bedrock in the highlands due to potential ground ice.

The undulated topography results in heterogeneous overburden thicknesses and ground ice formation. It is therefore expected that ice-rich conditions, which are very sensitive to thermal disturbance from construction activity or changes in climate, and bedrock, which is an ideal foundation, exist in close proximity.

3.10 TALOYOAK

Displacement Analysis

Two of the three Spotlight scenes over Taloyoak were acquired well into the winter, and exhibited significant land cover changes that marred the quality in all three resulting interferograms. An integrated motion layer was derived through weighted combination of all 3 interferograms; a noise floor of 8 mm and motion cluster threshold of 50 pixels was applied. The final motion layer was of limited value due to very high noise in the constituent layers.

Processing Notes / Known Issues

- Snow cover was present during the field work. The snow cover limited the information generated from surface roughness which is critical in identifying land cover and soil types
- DEM quality is limited and identifying lower areas where collection of water and moisture are more likely was limited

Suitability Analysis

The area has some undulated topography, but no major uplands. There is a structural lineament approximately orientated from southwest to northeast. The area of interest for the community of Taloyoak can basically be divided into two areas along the road that leaves from the air strip in a northeast direction. The north-western half is characterised by ponds, pattern ground, including ice-wedge polygons of different sizes, thermokarst features and few bedrock outcrops. These features indicate that ice-rich ground conditions exist in some areas of overburden, which are expected to be thick. It is also likely that ground ice will have a high saline content.

In contrast, the south-eastern half is more dominated by bedrock outcrops. It is expected that water and sediment would accumulate in the furrows and troughs of the bedrock, but it is generally believed that the ground ice content is much lower in those areas compared to the northern parts. Areas on the undulated bedrock that are currently classified as unsuitable because a pond formed, if located slightly elevated above the immediate terrain, may be suitable after the water has been drained and any thin sediment layers are removed. In the troughs between main bedrock ridges, however, ice-rich sediments likely accumulated and these zones should be avoided for development.

In general, the suitability map indicates larger areas that are unsuitable for development in the northwest than in the southeast.

3.11 REPULSE BAY

Displacement Analysis

Three Ultra-Fine scenes were acquired over Repulse Bay, resulting in 3 interferograms with average quality. Each pixel from each interferogram was weighted to generate an integrated motion layer, which exhibited significant signal along the coastline. Based on just 3 scenes, it was not possible to determine whether this signal was resulting from high soil moisture along the shore, or due to DEM height errors in the input CDED. Due to this ambiguity, we generated two separate motion layers that were incrementally applied during suitability analysis. These layers had a noise floor of 5 mm and 8 mm, and a cluster threshold of 100 pixels and 50 pixels respectively.

Suitability Analysis

Repulse Bay is surrounded by bedrock outcrops with very little thermokarst or other landforms that would indicate ice-rich conditions. The bedrock topography is characterized by north-northeast to south-southwest aligned structural lineaments. Sediments and water have accumulated in the lower troughs between linear bedrock ridges, which are exposed with very little overburden. This geological trend is also visible in the suitability map as ice-rich ground conditions, likely with high salinities, are mainly expected in the troughs.

Elevated areas of small ponds that are surrounded by bedrock may be suitable for development once the pond is drained and any overburden removed. Since these layers are likely very thin, limited effort is needed to prepare such areas for construction. However, massive ice can also form in bedrock by segregation and therefore the existence of ground ice cannot be ruled out anywhere in the study area. Also, although the bedrock areas are typically suitable for development, the possibility of climate-induced rising sea levels should be considered for lower elevation, coastal areas.

3.12 CAPE DORSET

Displacement Analysis

Cape Dorset was imaged by an Ultra-Fine stack comprising 14 images acquired over 18 months (May 2009 to November 2010). The majority of images were acquired during winter months when land cover changes due to freezing, snowfall, and snow melt limit the data quality. Nevertheless, since we had access to a voluminous stack of images, we were able to apply more advanced InSAR analysis than any of the other communities. We generated 91 interferograms by differencing all combinations of radar images. As expected, most of the interferograms exhibited poor quality due to substantial changes on the ground. Only about 5 of the interferograms exhibited high quality. We applied extremely strong filtering in order to offset the high noise manifest in the majority of interferograms.

The network of 91 interferograms was optimally solved in order to generate a high-quality interferogram for each acquisition date. The following temporal decontamination (Section 2.2.3) techniques were applied to the signal time series over each pixel:

- CDED Elevation Error over each pixel was minimized by statistically modeling the elevation error against the temporal distribution of interferogram baselines (satellite eye-distance)

- Short scale atmosphere, soil moisture, and residual height error were suppressed by applying a smoothing filter in the time domain. Since ground usually moves smoothly over time, this filter enhances the displacement signal at the expense of contaminants.

A time series of motion layers was derived (Section 6.3**Error! Reference source not found.**), and a linear regression was applied to compute an average ground movement velocity (mm/year) during the period of observation. A noise floor of 2 mm was applied to this velocity map to aid the ensuing terrain suitability analysis; this is the lowest noise floor among all 14 Nunavut communities, and is only possible because the high data volume enables us to appreciably decontaminate the signal. With 15 continuous RADARSAT-2 images containing no time gaps (acquired over 1 year), we can reach millimetre-level accuracy. Although Cape Dorset does not mimic this ideal dataset, we were still able to achieve a substantially lower noise floor through temporal signal decontamination.

Additionally, we used the highest-quality interferogram and the height error modeling to derive the difference between the external elevation model (CDED) and the true height. Hence, we were able to generate an improved DEM over Cape Dorset, with much better spatial resolution and vertical accuracy (Section 6.4).

Suitability Analysis

Cape Dorset is situated on the north end of Dorset Island, which is characterized by rugged bedrock terrain. As such, only a limited amount of ground ice is expected on the island. There is little overburden cover on the island; most is expected to be coarse-grained colluvium in the furrows and troughs between main bedrock ridges and fine-grained lacustrine sediments in and near ponds. In these areas, an increased amount of ground ice may exist.

There are few features visible from the optical images that would indicate ice-rich conditions. Even though no major polygons or thermokarsts are visible, there is patterned ground which could be indicative for ice-rich conditions. One such area with pattern ground exists as near a wet zone south and southeast of the air strip.

The rugged topography with steep bedrock slopes results in few areas having been identified to be suitable for development. However, it is suspected that it is the topography (i.e. steep slope angles) and not the actual foundation conditions are responsible for this classification. Therefore, there are many sections of bedrock slopes that are not necessarily unsuitable for development.

Another noteworthy area is the isthmus between Dorset Island and Malik Island. The isthmus is submerged at high tide and unsuitable for development. However, this area was identified as suitable for development likely because only winter data were available that did not identify water as the surface.

In general, ground ice cannot be ruled out for any area, including bedrock, and therefore local site investigations are needed before any decisions are made.

3.13 KIMMIRUT

Displacement Analysis

Kimmirut was imaged by three separate Spotlight (SL) RADARSAT-2 beam modes. The SL-3 and SL-26 beams only acquired a single image each (no pairs) and no InSAR processing was possible. Hence, the SL-76 stack, comprising two scenes from November 2010, was exclusively used for displacement analysis. The quality of the resulting single interferogram was very good, and it was converted into a motion layer. Since Kimmirut exhibits significant elevation relief, a lot of false motion clusters were overlying fore-slopes that are subject to geometric distortion (layover) in radar images. We constructed a layover mask and removed all false motion clusters. Since we only had access to a single interferogram, signal ambiguity from (short-scale) atmosphere, height error, and soil moisture could not be removed. We generated two motion layers with noise floors of 5 mm and 8 mm and cluster culling sizes of 100 pixels each. These layers were incrementally applied during terrain suitability analysis.

Suitability Analysis

Rugged terrain with bedrock outcrops elevated by more than 100 m above sea level characterises the area around the community of Kimmirut. Varying overburden thicknesses are expected. Hummocky and patterned ground, which has the potential for ice-rich conditions, appears to be prevalent in areas of thicker overburden. Such areas can mainly be found in troughs and furrows between bedrock ridges, that form drainage channels and ponds. An example can be found approximately 1.5 km southwest of the air strip.

Major thermokarst pond areas were not identified in the study area, which indicates that the overburden thickness is limited. It is expected that the ground ice in lowland areas will have high salinity, which reduces the freezing point and allows the permafrost to degrade faster.

In general, little sediments are expected in and around the ponds that formed in the several local depressions of the irregular and elevated bedrock surface. Hence little ground ice, if any, likely exists and these areas, which may be suitable for development, even though they were classified as unsuitable in the general algorithm. Bedrock outcrops at lower elevations are generally less suited for development compared to the bedrock in the highlands due to potential ground ice. To better understand potential local ground ice conditions, which may also form in the bedrock areas, geotechnical site investigation must be carried out before any development planning commences. The rugged topography significantly reduces the informative value of the suitability classes presented for Kimmirut and are therefore to be considered as general guidance only.

3.14 POND INLET

Displacement Analysis

Pond inlet had a sole SL-71 scene that could not be used for InSAR processing. It was additionally imaged by a SL-21 beam comprising two images that were acquired 72 days apart. Due to the long time-gap between acquisitions, substantial land cover changes occurred that led to poor quality in the resulting interferogram. Moreover, significant short-scale atmospheric signal was observed in this interferogram, which was transferred directly into the derivate motion layer. Hence, a relatively high noise floor (8 mm) and cluster removal threshold (100 pixels) was applied to generate the final motion layer, which contained negligible signal with low confidence.

Processing Notes / Known Issues

- An image acquisition was lost (conflict) causing a long gap between the September and November acquisitions
- The May 16, 2009 Image acquisition was used only for interpretation
- Many steep slopes throughout the AOI, reducing suitability

Suitability Analysis

Topography plays an important role in the suitability for development around the community of Pond Inlet. Ice-rich conditions, with ground likely containing significant salinity, are expected in the lower elevations that surround the current community. In particular, the area west of the airstrip to the coast likely is very ice-rich, and ice-wedge polygons are evident on the optical images. However, in this location, the remote sensing techniques have identified part of this area as "suitable for development". Because of the limitations of the methodology, it is possible that several lowland areas identified as "suitable for development" are, in fact, only limited or marginal suitable for future development. Also, lowland areas that clearly show drainage channels on optical imagery should be considered as only "marginally suitable" for development. It is therefore imperative that local investigations be carried out before any development planning commences.

Even though the plain, in which Pond inlet is situated, increases slightly in elevation towards the south-east, it is generally thought to be a flood plain fed by several glaciers and therefore consist of considerable amount of sediments. Patterned ground, thermokarst and the creek pattern indicate that the ground likely contains significant amount of ground ice. The landscape seems to be very dynamic, indicating ice segregation and thermokarst events most likely in combination with the ice-rich permafrost conditions that are expected to dominate. It is expected that with distance from the shoreline the salinity decreases and freshwater ice dominates, which has better strength characteristics than saline frozen ground.

Ice-rich foundation conditions are expected to dominate throughout the area of interest around Pond Inlet, and specific site investigations are strongly recommended before any development planning commences.

4.0 DELIVERABLE FORMATS

All file delivered in UTM NAD83, CSRS coordinate system.

4.1 DEVELOPMENT SUITABILITY MAPS

All community development suitability maps are delivered in the following format:

- AutoCAD Files – dwg (2007) identifying each suitability class as a separate layer.
- Shapefile format – ArcGIS shapefile

4.2 RADARSAT-2 DATA

Each image is delivered as an 8-bit Geotiff. 16-bit Geotiff files are also provided.

5.0 CONCLUSIONS

This project demonstrated the value of using remote sensing techniques in combination with permafrost expertise to evaluate the suitability of ground conditions for future development. Radar data has some significant advantages for monitoring in the Canadian arctic:

- Generate images regardless of cloud cover or light conditions
- Optimal for monitoring ice / open water
- Radar is the only satellite option for generating displacement measurements
- Radar data can effectively generate DEMs over large areas
- RADARSAT-2 data is available for low to no cost through Government of Canada Programs
- Radar data covers large areas extending beyond built-up areas of the Nunavut communities

When image acquisition conditions were good, RADARSAT-2 data was shown to be an effective tool for evaluating land cover and identifying areas of displacement. This data combined with the other indicators can be used to help planners identify the development suitability of areas near the communities.

While this project showed that deriving suitability maps from RADARSAT-2 data could be effective, there were important considerations for maximizing the derived information. Radar data is effective when comparing data from multi-temporal acquisitions; during this project, the most valuable information was generated from data acquired during the summer and fall. Winter images were not effective in separating ground cover classes and the quality of displacement data was limited due to the snow cover. Radar data can penetrate through dry snow however if the snow layer is thick or contains moisture, most underlying features will be obscured. Snow cover affected the quality of data generated from images acquired in October and later into the winter. The image acquisitions only began in mid-September and there was snow cover in all imagery over some communities, significantly limiting the ability to determine permafrost indicators from remote sensing data. Winter conditions restricted the ability to determine:

- land cover classifications
- water/land boundaries
- drainage / presence of soil moisture
- displacement measurements

Ground movements in permafrost terrains are either associated with freeze-thaw cycles in spring and fall, or thaw consolidation settlements and frost heave during summer and winter, respectively. In addition, these deformations can be very slow and may therefore not be captured if the RADARSAT-2 images over a short time span. By extending the observation period and adding more images to the series, it will be possible to obtain a much better appreciation of the landscape's dynamics.

The quality of Development Suitability at communities where only winter imagery was acquired (Chesterfield Inlet, Kimmirut) was not as strong. The timing of data acquisitions is extremely important to avoid conflicts with the Canadian Ice Service and to acquire the most effective data.

Measuring displacement from radar data is only possible when the ground cover remains stable and vegetation and/or snow do not create noise for the interferometric measurements. In many of the communities (Cambridge Bay, Cape Dorset, Sanikiluaq), the data quality was strong enough to identify areas of displacement and RADARSAT-2 was shown to be an effective tool. Moreover, continuing image acquisitions over a community incrementally improve the quality and accuracy of displacement information, as demonstrated for the Cape Dorset dataset (Section 6.3). Seasonal motion phenomena can also be studied once a multi-year dataset has been collected.

However, the suitability for development will always depend on the foundation conditions, in particular the ground ice content. Remote sensing will only provide information on the surface conditions as well as surface deformations, but not directly on the ground ice content. Latter will always have to be interpreted based on the ground surface signal. Remote sensing tools are therefore very valuable for general development planning, but should not be used for any foundation design, where site specific investigations must be carried out. This study was completed using predominantly winter satellite imagery, which limits its utility in terms of conclusively classifying the development suitability of each community. It is therefore recommended that local investigations be carried out before any development commences. The development suitability layers supplied provide general guidance, and serve as screen tools prior to targeted geotechnical assessment of the foundation conditions.

6.0 RECOMMENDATIONS

Based on the conclusions, this section provides recommendations to the GN in light of the analysis, observations, and constraints pertaining to this project.

6.1 SITE SELECTION

Terrain Suitability Analysis is more pertinent for communities with soil surface layers. Areas with greater bedrock are more likely to be stable, with fewer areas of displacement and fewer permafrost features present. Hence, it is recommended that future analysis focus on sites that are not dominated with bedrock. Sites like Cambridge Bay and Hall Beach are more likely to require regular monitoring. Reconnaissance of previously unknown displacement is closely tied to the timing of data acquisition, which is discussed below.

6.2 RADARSAT-2 DATA ACQUISITION

The winter timing and limited volume of data were the major constraints within this project. RADARSAT-2 data acquired during winter exhibits significant snow cover that makes it difficult to delineate water bodies, classify land, identify features, and monitor ground movement (which is already limited during the cold season). Additionally, the CIS acquires significant data during winter for Sea Ice Monitoring, which resulted in frequent conflicts with our data acquisitions. Conflicts with the CIS can be expected with any future monitoring programs during the winter. The amplitude images and interferograms generated using summer acquisitions were vastly superior to those based on winter acquisitions. Also, datasets with more images (Cape Dorset and Cambridge Bay) yielded better results.

We recommend to the GN to continue data acquisition at priority sites, with emphasis on summer scenes. The continued acquisitions will improve accuracy of ground movement monitoring, and seasonal freeze/thaw cycles will be better characterized with acquisitions in the summer. The higher-quality summer images will also support better land classification and feature identification, thereby generating better terrain suitability maps. We also recommend using the Spotlight (1.6 m resolution, 18 km x 8 km coverage) beam rather than Ultra-Fine (3 m resolution, 20 km x 20 km coverage) beam due to the former's superior resolution and signal quality. The Ultra-Fine beam should only be used when a single Spotlight image does not provide full coverage over the desired AOI. Spotlight modes have a higher cost and this should also be considered.

New image acquisitions can be integrated with existing data sets for more comprehensive analysis of land cover and ground displacement changes.

6.3 CONTINUED MONITORING

Cape Dorset was the only community with a multi-year data stack, containing 14 images acquired over 18 months (May 2009 to November 2010). Although most of the summer acquisitions were missed, we still applied advanced temporal decontamination techniques (Section 2.2.3) to the stack. We successfully separated ground movement from contaminating signals such as atmosphere, soil moisture, and elevation error. Figure 18 illustrates the main displacement basins identified over the Cape Dorset dataset, including three subsidence zones and one uplift zone. In addition to mapping the spatial extents of each displacement basin, we also characterized the temporal evolution of the motion signal for each basin. Figure 19 illustrates the displacement history for a selected point in a subsidence zone. Figure 20 illustrates the displacement history for a selected point in the uplift zone.

It is likely that the three subsidence sites are associated with thermokarst / permafrost degradation (situated close to water bodies), whereas the uplift may be segregation, i.e. formation of massive ice in the ground.

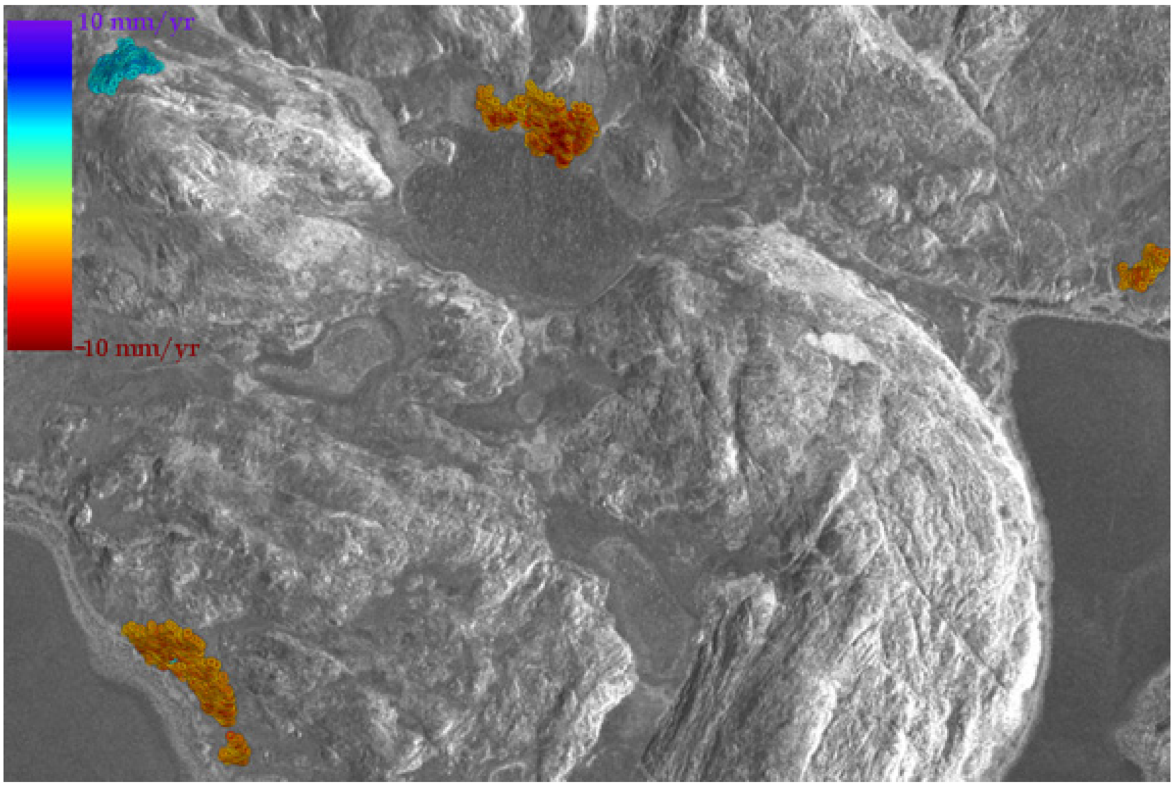


Figure 18 Spatial extents of displacement basins - Cape Dorset

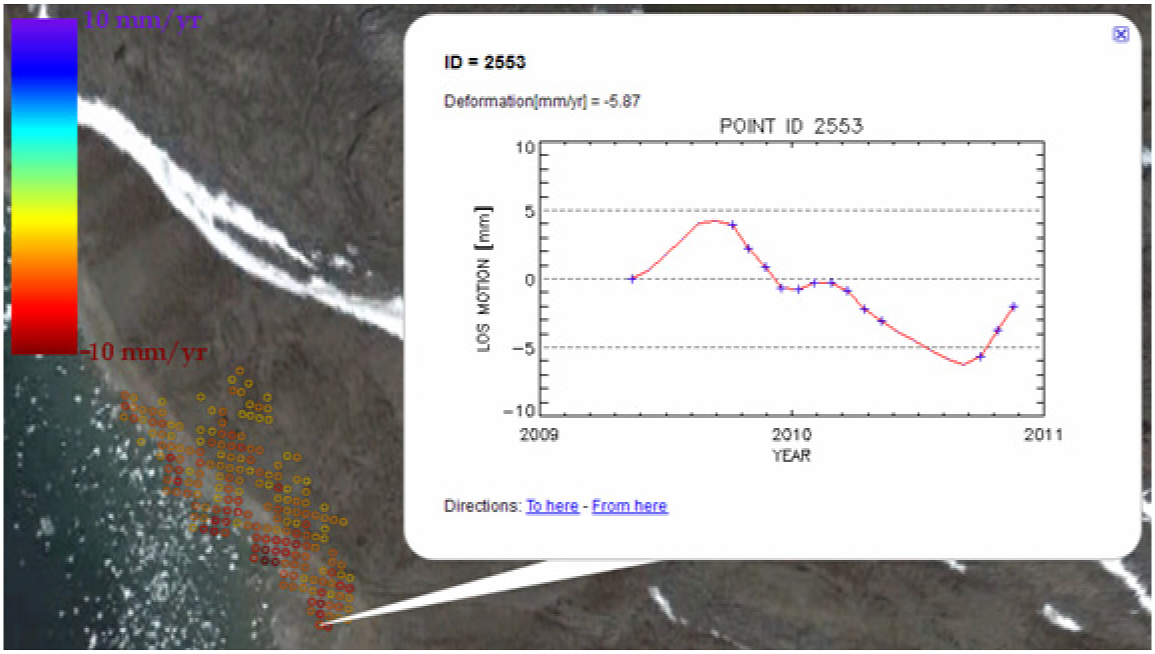


Figure 19 Displacement history of a point in a Subsidence Zone – Cape Dorset

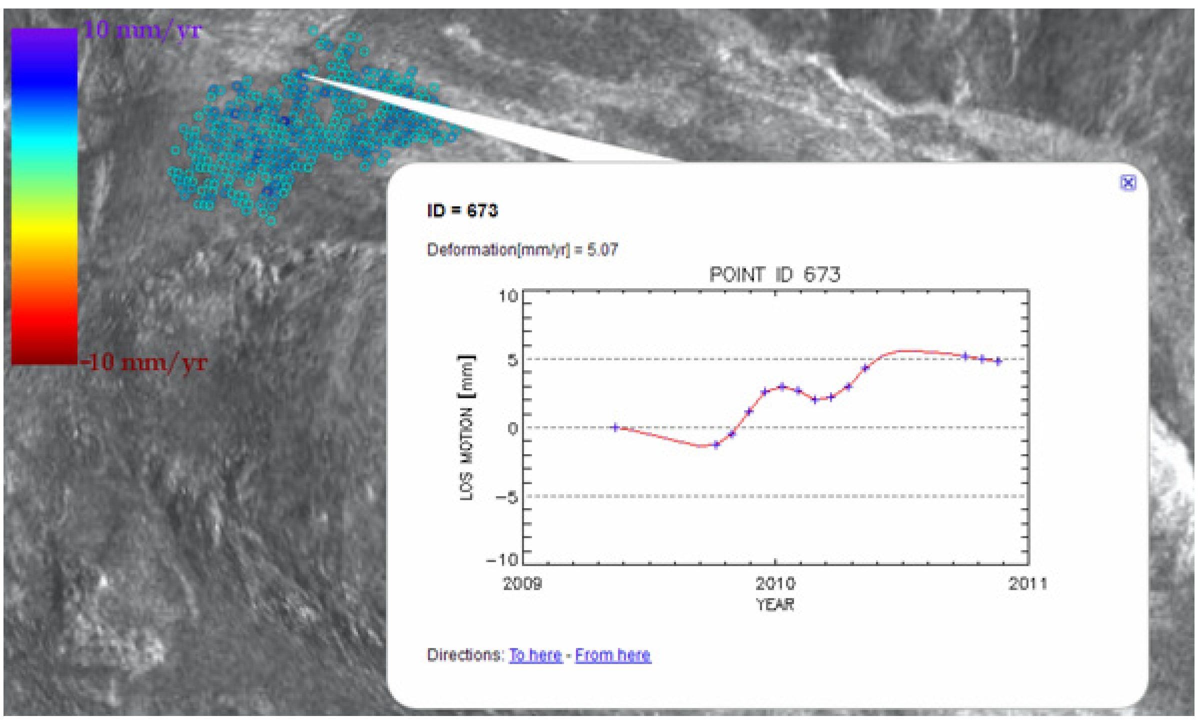


Figure 20 Displacement history of a point in an Uplift Zone – Cape Dorset

If the GN continues acquiring data over other priority sites, it will be possible to develop similar advanced ground movement products for other communities as well. This will support better analysis of terrain suitability for future development and to identify potential geohazards before they damage property and people.

Figure 21 Landslide at Pond Inlet, 2010 (Courtesy Paul Compton)

Figure 21 shows a landslide that occurred at Pond Inlet during the summer of 2010. While no data was acquired prior to the landslide, RADARSAT-2 monitoring can be used to identify landslides and other geohazards that can cause significant damage. With sub-cm accuracy, monitoring ground displacement with radar can detect small displacement activity before a significant failure occurs. Changing permafrost conditions surrounding the communities in Nunavut will likely increase the potential for geohazard impact.

6.4 DEM IMPROVEMENT

One of the constraints encountered in this project was the poor resolution, low vertical accuracy, or artefacts (Section 2.1.2) in external elevation data. InSAR is sensitive to ground elevation, with two main constraints:

- High quality is required, which usually results from summer acquisitions when land cover changes are minimal
- Appropriate satellite eye-distance (baseline) between the observations is needed

Both conditions are usually met by one or more pairs of images within a large dataset such as Cape Dorset. It then becomes possible to improve the external DEM using InSAR. We utilized one of the 91 interferograms in the Cape Dorset dataset to create a high-resolution DEM. Figure 22 compares CDED against the RADARSAT-2 DEM that we generated. The latter has greater spatial detail and land features are better delineated. Note that hydrographic correction has not been applied to the RADARSAT-2 DEM.

High resolution DEMs, which may also be acquired locally using LiDAR (although at a significant cost) or high definition stereo satellite images, would allow for an improved topographical criterion to be incorporated. It would, for example, be possible to better differentiate between possible thermokarst features that are likely to occur in close proximities to water bodies, and simply rough bedrock topography. Depending on the DEM resolution, it might even be possible to extract regular pattern, such as ice-wedge polygons, hummocks or patterned ground, which are indicators for ice-rich grounds.

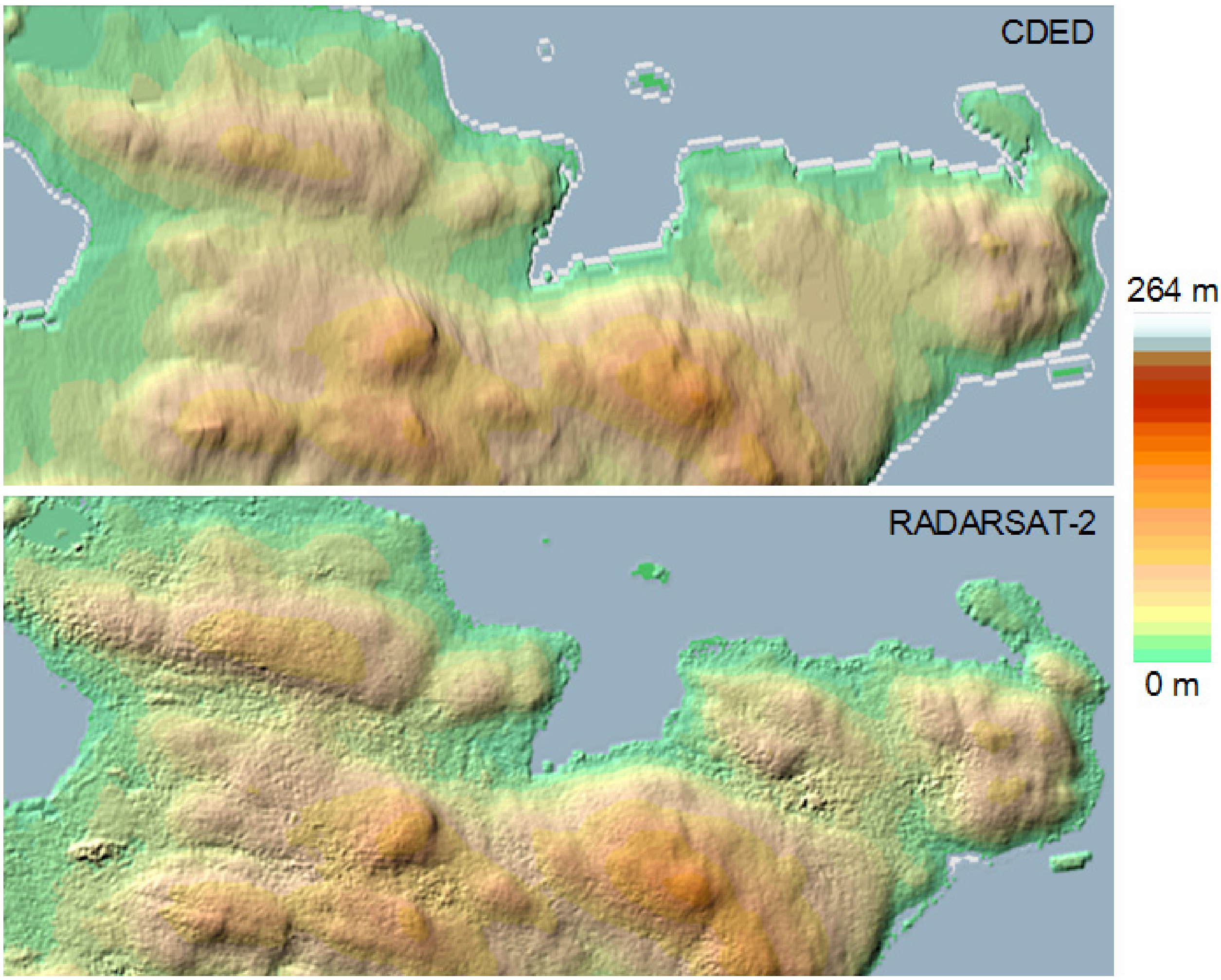


Figure 22 DEM Improvement using InSAR – North of Cape Dorset

If the GN continues data acquisition over priority sites (especially during the summer), it is very likely that one or more interferograms would be conducive for improving the existing DEM. Hence, a higher-resolution and more accurate DEM could be generated, which would support better terrain suitability analysis and also other important applications unrelated to this project.

6.5 LAND COVER IMPROVEMENTS

The surface land cover is one of the most critical elements in the assessment. Remote sensing data currently available did not allow for determining the various land covers in detail. This could not be achieved because of the timing of the data available as well as the technologies used. Multi-spectral, high resolution images taken during the summer months would likely allow for such a detailed analysis that may then be used in combination with displacement information generated from RADARSAT-2 data and improved DEMs to better assess the suitability for development.

7.0 LIST OF ACRONYMS

3vG	3v Geomatics Inc.
AOI	Area of Interest
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BGC	BGC Engineering Inc.
CDED	Canadian Digital Elevation Data
CIS	Canadian Ice Service
CSA	Canadian Space Agency
CSRS	Canadian Spatial Reference System
CTIS	Centre for Topographic Information (Sherbrooke)
DEM	Digital Elevation Model
EO	Earth Observation
GIS	Geographical Information System
GN	Government of Nunavut
GNWT	Government of Northwest Territories
INAC	Indian and Northern Affairs Canada
InSAR	Interferometric Synthetic Aperture Radar
JPEG	Joint Photographic Experts Group
LOS	Line Of Sight
NWT	Northwest Territories
R&D	Research and Development
RADAR	Radio Detection and Ranging
RADARSAT-1	Canada's first SAR satellite launched in November 1995
RADARSAT-2	Canada's second SAR satellite launched in December 2007
RFP	Request for Proposal
SAR	Synthetic Aperture RADAR
SL	Spotlight
SRTM	Shuttle Radar Topography Mission
UF	Ultra-Fine
UTM	Universal Transverse Mercator

APPENDIX A

Optical Satellite Imagery:

World View- Satellite Images:
• Rankin Inlet
• Cambridge Bay
• Cape Dorset
For the communities noted above there are base maps that include contours and DEMs that cover the built up area of the communities in AutoCAD format.

Geo Eye-1 Satellite Images:
• Hall Beach
• Gjoa Haven
• Taloyoak
• Chesterfield Inlet
For the communities noted above there are base maps that include contours and DEMs that cover the Project Area Option A.

Quick Bird Satellite Images:
2006 Quick Bird Satellite Images exist for all communities. Each community, other than the communities covered by the Geo Eye Satellite image, there are DEMs and Contours that cover the built up area of the communities.