Natural Resources Canada
Ressources naturelles Canada

GEOMATICS CANADA
OPEN FILE 30

RADARSAT Constellation Mission DInSAR potential in permafrost terrain

N.H. Short

2017

Canada

GEOMATICS CANADA
OPEN FILE 30

RADARSAT Constellation Mission DInSAR potential in permafrost terrain

N.H. Short

2017

doi:10.4095/300078

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation
Short, N.H., 2017. RADARSAT Constellation Mission DInSAR potential in permafrost terrain; Geomatics Canada, Open File 30, 22 p. doi:10.4095/300078

Publications in this series have not been edited; they are released as submitted by the author.

Executive Summary

Differential Interferometric Synthetic Aperture Radar (DInSAR) has proven itself to be a valuable source of information about terrain stability in permafrost regions over the last half decade. DInSAR uses differences in the phase information of repeat pass radar acquisitions to detect movement of the ground at the millimetre to centimetre scale. Terrain stability maps have been enthusiastically received and adopted by infrastructure planners and managers across Canada's northern regions. To date, most terrain stability maps have been generated using radar data from the Canadian RADARSAT-2 satellite. The RADARSAT Constellation Mission (RCM) is the planned replacement for RADARSAT-2 and is scheduled for launch in 2018. This study considers the RCM mission characteristics and explores what it might deliver in terms of terrain stability information for permafrost regions.

The RCM innovation over RADARSAT-2 is that there will be three identical SAR satellites, evenly spaced, in a common orbit. This will enable interferometric acquisitions with a rapid, four day, revisit interval. Preliminary results show that the rapid revisit interval can be expected to deliver better stack products, with better signal to noise ratios and cleaner, more complete and more reliable maps of seasonal terrain displacement, particularly when high resolution beam modes are used. Agreement with ground measurements is also likely to be closer, although these might still not be an exact match for reasons that are not yet fully understood. A significant advantage of the four day revisit interval is not just better coherence and more accurate data in itself, but an increased number of observations, such that poor data sets can be excluded without noticeably compromising the duration or density of the stack.

In contrast to RADARSAT-2, where users could request specific SAR acquisitions at specific locations, RCM will adopt a 'Standard Coverage' approach, where large scale acquisition strategies using specific beam modes are preprogrammed to systematically cover Canada. With the Standard Coverage beam modes being chosen to support large scale operational SAR data users. The RCM Standard Coverage approach could be severely limiting for the permafrost application. While Spotlight data consistently produce excellent results, lower resolution Fine and Ultra-fine products are not so reliable. Coarser resolutions miss the details of the natural terrain and suffer from lower coherence levels, which has implications for the reliability of the phase unwrapping and the accuracy of derived displacement products. It is not yet known to what extent the shortened revisit interval will compensate for the disadvantages of lower resolution data. However, even if the coherence and phase problems identified here can be overcome, all the RCM medium resolution beam modes (16, 30 and 50 m) will miss details in the landscape and are well below the scale that infrastructure planners, managers and engineers require.

Table of Contents

List of Tables

List of Figures

1. Background

Differential Interferometric Synthetic Aperture Radar (DInSAR) has been proven to be a useful technique to detect ground movement in permafrost regions (Liu et al., 2010; Short et al., 2011; Short et al., 2012; Strozzi et al., 2012; Short et al., 2014). Ground movement in permafrost terrain may be the result of seasonal processes, such as thaw and settlement or freeze and heave of the active layer, or may be the result of long term permafrost thaw due to anthropogenic or climate factors. Patterns of seasonal ground movement are of interest in understanding terrain stability and for planning appropriate land use and infrastructure construction. Long term patterns of movement are useful for understanding areas of long term risk to infrastructure, as well as environmental change, including vegetation and potential carbon storage change. Ground validation has shown that the greatest seasonal patterns of movement often correspond with areas experiencing long term change due to changes deep in the permafrost (Wolfe et al., 2014). Therefore, just a short observation period can in fact deliver information about short and long term change. High resolution DInSAR, ~ 1 m horizontal resolution, has shown that the surface displacement patterns correlate very well with surficial geology and the results of resistivity surveys of the shallow subsurface (3-6 m depth) (Short et al., 2014). Resistivity surveys detect the degree to which the ground is frozen and identify areas that are unfrozen, have unfrozen water content within the permafrost, or have high saline concentrations. The resistivity surveys and the correlated DInSAR patterns can be used to understand subsurface water flows and identify areas of permafrost that are close to thawing and that pose risks to infrastructure (Short et al., 2014).

RADARSAT-2, the Canadian radar satellite launched in 2008, has made a major contribution to this application over the last nine years. Given the immediate and obvious value of DInSAR terrain stability products in northern infrastructure planning and management, this study was undertaken to explore the potential contributions of the upcoming RADARSAT Constellation Mission (RCM) to this permafrost application. RCM is scheduled for launch in July 2018 and is the designated radar data continuity mission for Canada.

2. RCM Study Objectives

The RADARSAT Constellation Mission (RCM) will be comprised of three identical radar satellites. These satellites will be evenly spaced in a common orbit, which will facilitate a four day interferometric revisit interval. A four day revisit interval should dramatically improve interferometric coherence, i.e. the quality of DInSAR measurements. The RCM will however, be managed differently than its RADARSAT predecessors. Instead of users ordering the data of their choice, they will be constrained to 'Standard Coverages'. These are consistent and fixed modes of operation over defined areas. This strategy should reduce user and acquisition conflicts and permit an archive with many more repeat passes suitable for interferometry and change detection. However, the use of Standard Coverages will make the acquisition of very high resolution data more difficult. Standard Coverages are designed to support the requirements of high data volume operational users for whom medium and low resolution data offer better coverage for wide area monitoring.

The objectives of this study were:

1. To explore the rapid revisit potential of RCM using data from the COSMO-SkyMed SAR satellite constellation as demonstration, i.e. to simulate a four day interferometric revisit interval.

2. To explore the impact of the Standard Coverage approach on the permafrost application, by evaluating the information content of lower resolution DInSAR products.

To optimize effort and the delivery of useful products, test sites were chosen that aligned with on-going work of Natural Resources Canada (NRCan). Iqaluit in Nunavut was used for the COSMO-SkyMed rapid revisit simulation, as it was a site with on-going instrumentation and detailed knowledge of ground conditions. Rankin Inlet, also in Nunavut, was selected as the site for the lower resolution data test. This was a new NRCan site where it would be easier to begin the acquisition of new interferometric data stacks. Figure 1 shows the locations of these two test sites.

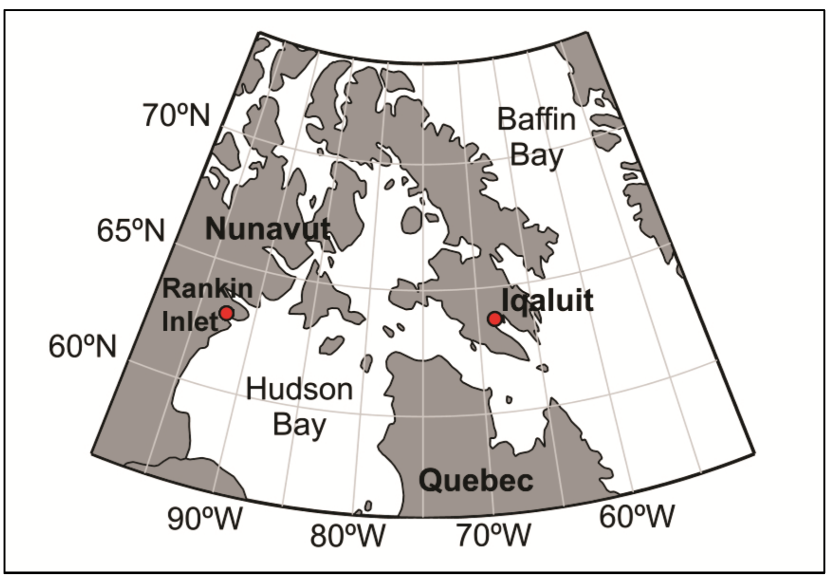


Figure 1. Low Arctic of eastern Canada showing the locations of Iqaluit and Rankin Inlet.

3. Data

For the four day rapid revisit simulation COSMO-SkyMed (CSK) data were obtained through the Canadian Space Agency (CSA) – Agenzia Spaziale Italiana (ASI) data exchange agreement. ASI provided 27 scenes in 2014, with acquisitions obtained with 1-9 day separations, and 20 acquisitions in 2015, with 4-16 day separations. Spotlight mode was used in order to compare the results directly with the Spotlight RADARSAT-2 data already being collected over Iqaluit. Table 1 lists the SAR acquisitions used in the Iqaluit DInSAR processing. Note that the number of scenes used might differ from the total scenes acquired since snow-covered scenes were excluded from processing.

Table 1. Iqaluit COSMO-SkyMed and RADARSAT-2 acquisitions

CSK 2014	RADARSAT-2 2014 (SLA18)	CSK 2015	RADARSAT-2 2015 (SLA18)
20140610	20140513	20150613	20150601
20140618	20140606	20150621	20150625
20140626	20140630	20150625	20150719
20140704	20140724	20150629	20150812
20140705	20140817	20150707	20150905
20140712	20140910	20150711	
20140720		20150715	
20140721		20150723	
20140724		20150727	
20140728		20150731	
20140805		20150808	
20140813		20150812	
20140821		20150816	
20140822		20150901	
20140829		20150909	
20140906		20150913	
20140914		20150917	
20140922		20150925	
20140923		20151003	
20140930			

For the Standard Coverage evaluation five RADARSAT-2 data stacks were acquired over Rankin Inlet. Table 2 lists the modes and acquisition dates of the radar acquisitions. The Spotlight data have 1 m resolution, Ultra-fine data 3 m resolution and Fine mode 10 m resolution. Acquisition years were 2015 and 2016.

Table 2. Rankin Inlet RADARSAT-2 acquisitions

Spotlight (SLA23)	Spotlight (SLA23)	Ultra-fine (U26)	Ultra-fine Wide (U18W2)	Fine (F23)
20150529	20160523	20160527	20150522	20160520
20150622		20160620	20150615	20160613
20150716	20160710	20160714	20150709	20160707
20150809	20160803	20160807	20150802	20160731
20150902	20160827	20160831	20150826	20160824
	20160920	20160924	20130912	20160917

A high resolution digital elevation model (DEM) has been shown to be critical in deriving intelligent DInSAR displacement products with relatively small numbers of interferometric scenes and when displacement signals are small (< 3 cm) (Short et al., 2009). High resolution DEMs (1 m horizontal resolution, 30 – 50 cm vertical accuracy), derived from stereo-optical satellite data, were used for the Iqaluit and Rankin Inlet DInSAR processing.

4. Methods

DInSAR processing was carried out using the GAMMA SAR processing software (Werner et al., 2000). Processing followed the conventional steps of scene co-registration, interferogram formation, flat Earth phase removal, topographic phase simulation and removal using an external DEM, phase filtering (Goldstein and Werner, 1998), phase unwrapping (Costantini, 1998), baseline refinement, and stacking (Lyons and Sandwell, 2003), to extract a linear displacement trend for the summer period of observation. The trend was converted from radar line-of-sight to vertical displacement using the satellite geometry and geocoded to a UTM projection, to facilitate GIS analysis with ancillary data. Further details on this processing approach including the stacking algorithm are available in Short et al. (2014).

In addition to the DInSAR stacking approach and the production of maps of seasonal ground displacement, a time series analysis was undertaken for specific points in the Iqaluit data sets, to enable point comparisons with field measurements. The Iqaluit site had two thaw tubes, an Automatic Weather Station (AWS) and a network of water-level loggers, with field measurements made at regular intervals throughout the summer. The ground displacement measurements in consecutive DInSAR pairs at these locations were extracted and plotted against the field measurements in graph format.

5. Results

5.1 Simulating RCM Rapid revisit – Iqaluit Airport

Figure 2 shows the ground displacement result for the 2014 CSK Iqaluit Airport data stack. Figure 3 shows the identical area and the RADARSAT-2 2014 stack product. Processing is virtually identical, the only difference is that the CSK product has 22 input acquisitions whereas the RADARSAT-2 product has only 6 inputs.

The CSK products are overall smoother, i.e. less noisy, and more complete, this is most noticeable in the runway coverage but also noticeable over the terrain in general. This may be a combination of two factors. Firstly, the CSK SARs have an X-band, 3.11 cm wavelength, this will be more sensitive to the roughness of the runway and therefore more likely to obtain a signal over a smooth asphalt surface, compared to the 5.5 cm wavelength of the RADARSAT-2 C-band SAR. Secondly, the rapid revisit interval (<12 days) will obviously maintain coherence in CSK pairs much better than in RADARSAT-2 pairs (24 days). More complete and less noisy displacement maps are thus an expected result from the rapid revisit interval of RCM. While satisfactory displacement maps can be generated from longer revisit interval data by employing filtering and interpolation methods, less post processing is required to produce good displacement maps when short revisit interval data are used.

Figures 4 and 5 show the CSK and the RADARSAT-2 displacement products for 2015 respectively. As in 2014, the CSK product is smoother, cleaner and more complete than the RADARSAT-2. Despite the differences in data acquisitions, regions and features of stability and instability are generally well identified and commonly located in both data sets. The reduced amount of settlement in 2015 compared to 2014 is captured by both satellites. In 2014 and to some extent in 2015, the RADARSAT-2 data suggest greater amounts of displacement than the CSK, this is likely a consequence of the timing of the RADARSAT-2 acquisitions which began 12 – 20 days prior to the CSK acquisitions. The late May and early June period is very important for seasonal thaw and so the earlier RADARSAT-2 data would have captured increased amounts of thaw settlement. Although the CSK data extend later into the autumn, there would be little to no thaw settlement occurring at that time, thus the CSK derived displacement trend would be subdued.

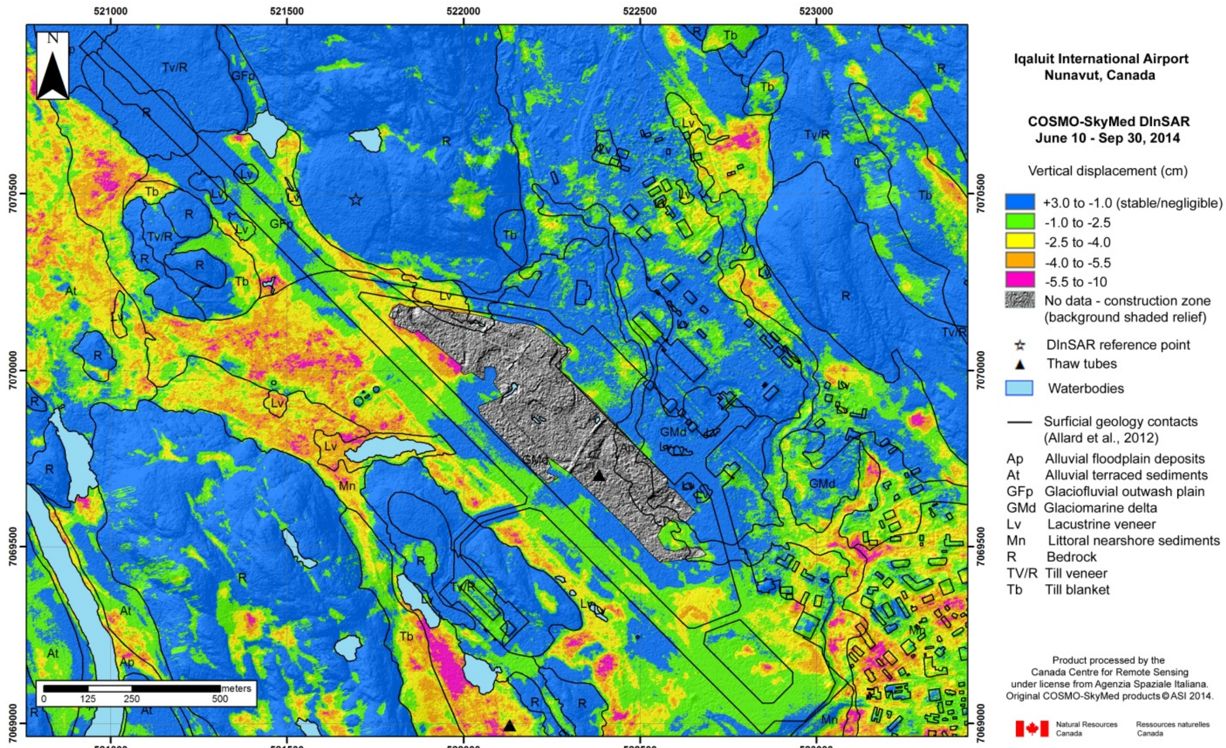


Figure 2. COSMO-SkyMed DInSAR derived displacement for Iqaluit Airport from summer 2014. A large construction project took place at the airport beginning in July, 2014, the affected area has been excluded to remove misleading results.

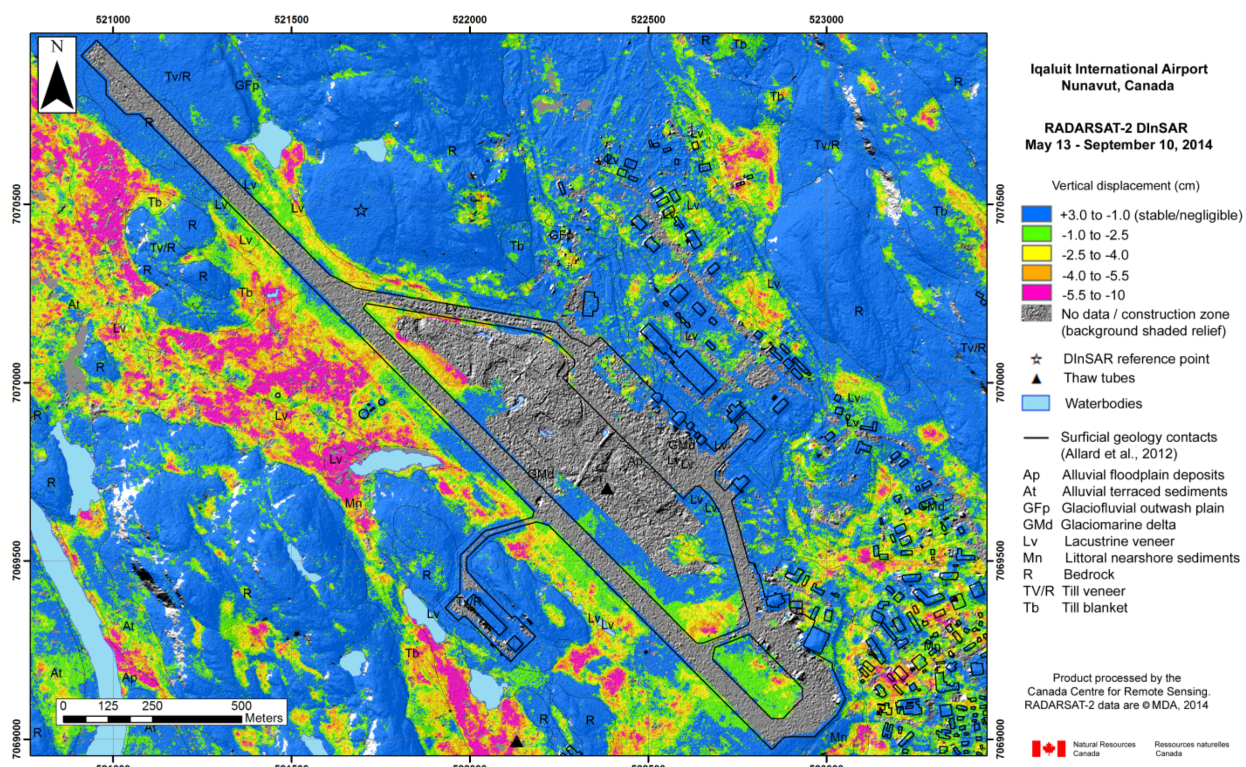


Figure 3. RADARSAT-2 Spotlight 18 DInSAR derived displacement for Iqaluit Airport from summer 2014. Results are excluded from the active construction area between the airport runway and apron.

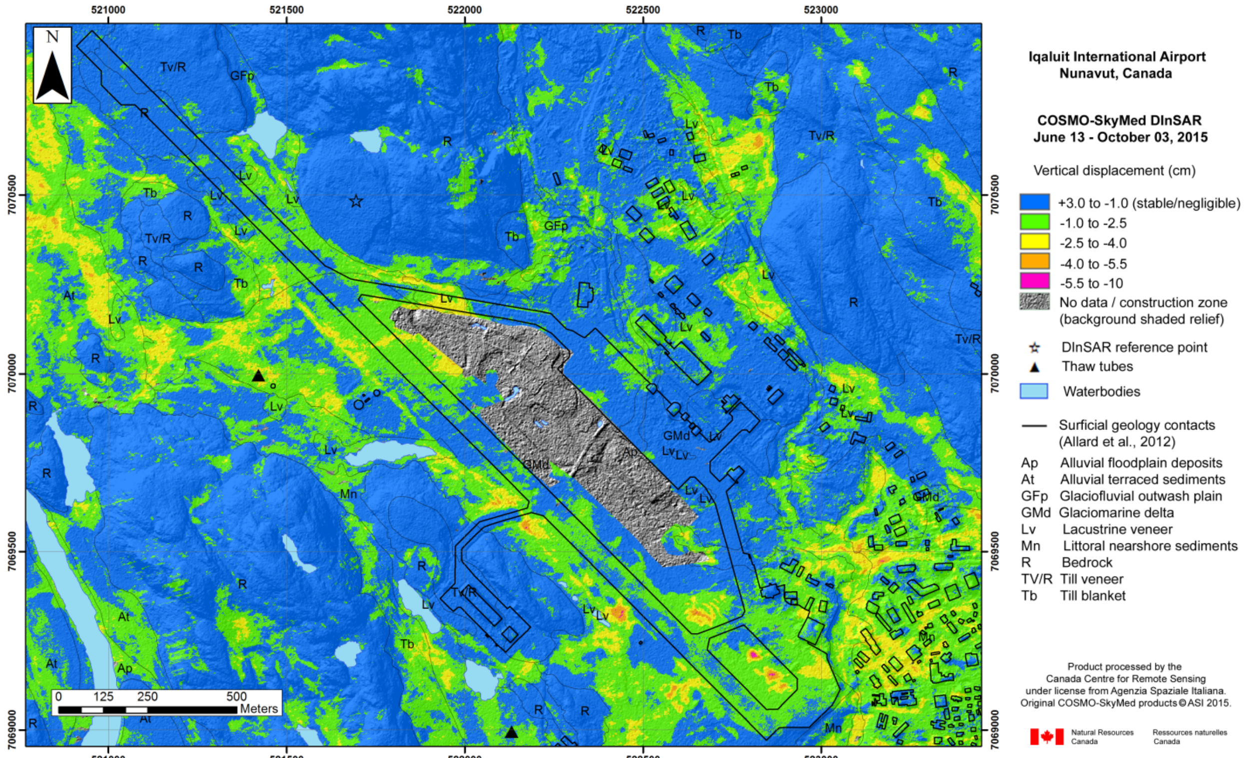


Figure 4. COSMO-SkyMed DInSAR displacement for Iqaluit Airport from summer 2015. Results have been excluded for the active construction area between the runway and the apron.

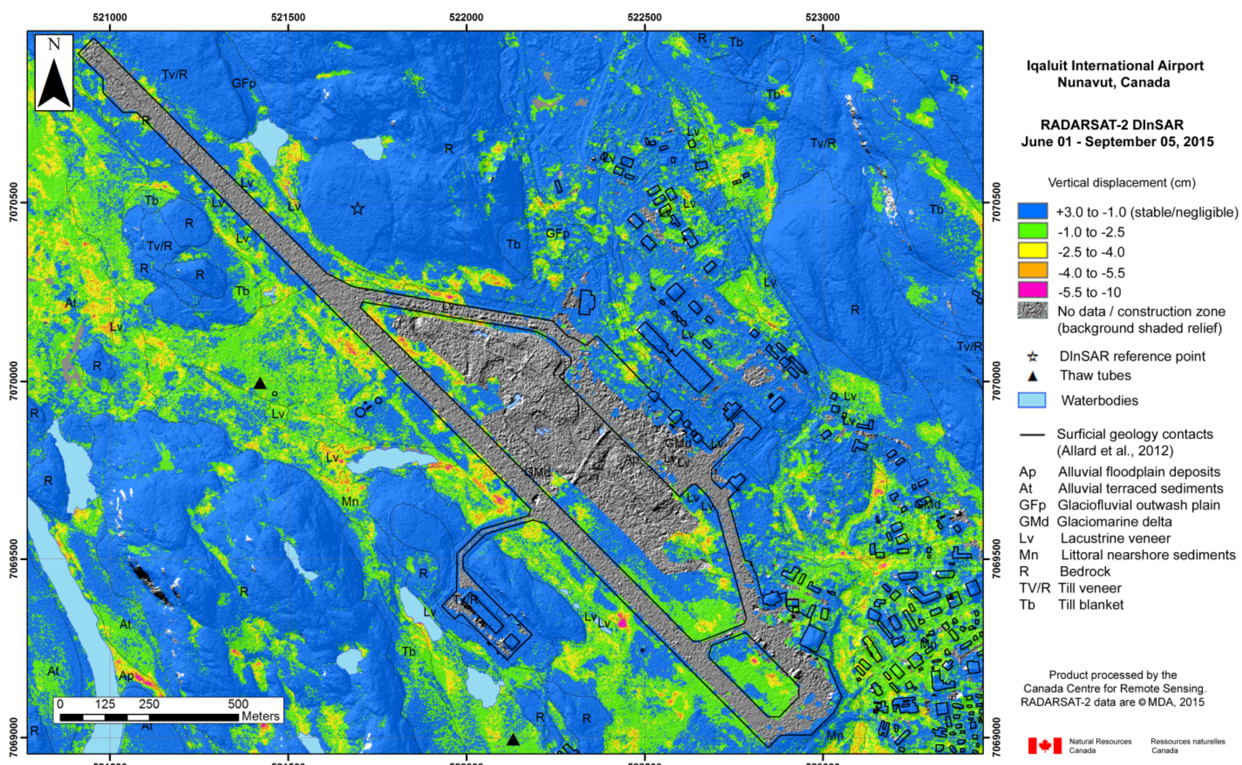


Figure 5. RADARSAT-2 Spotlight 18 DInSAR displacement for Iqaluit Airport from summer 2015. Results have been excluded from the active construction area between the runway and the apron.

5.1.1 Iqaluit time series

Figures 6 and 7 show plots of thaw tube and DInSAR measurements of ground displacement in 2014. The locations of the 2014 Airport and Sylvia Grinnell Park thaw tubes can be seen in Figures 2 and 3.

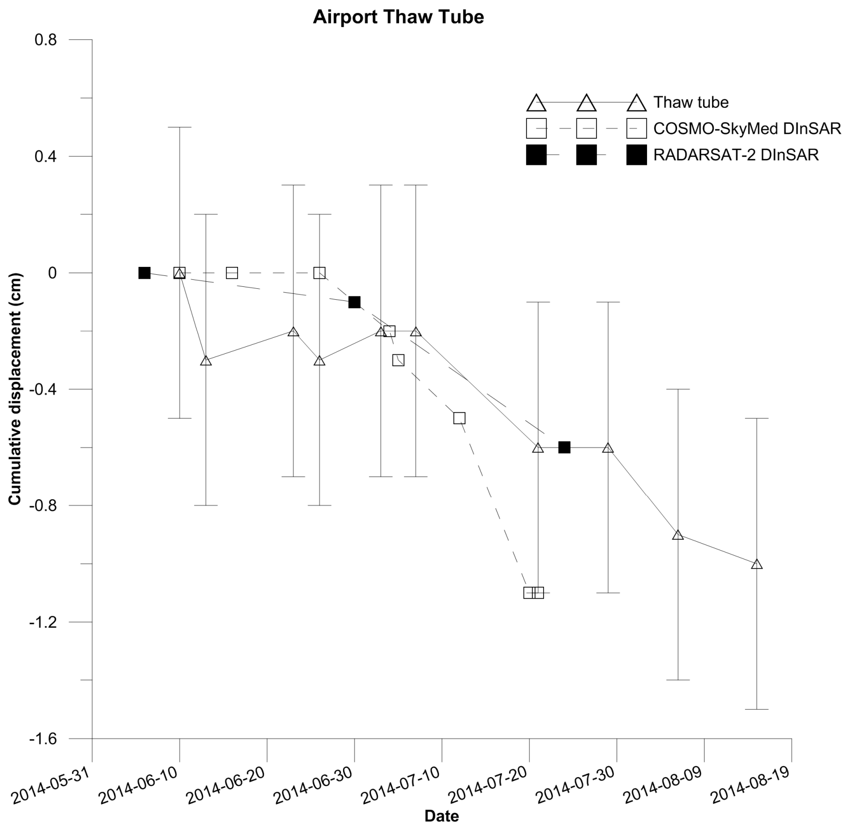


Figure 6. Iqaluit Airport thaw tube measurements with CSK and RADARSAT-2 DInSAR results from summer 2014. Note that due to a large airport construction project this thaw tube was removed in August. Construction disturbance of the surrounding terrain began on July 7.

At the low displacement Airport thaw tube (<2 cm/summer) the DInSAR measurements agree with the field data to within 0.5 cm, the margin of error for the field measurements. The CSK results show slightly more variability than the RADARSAT-2, and neither satellite captures the displacement perfectly, although RADARSAT-2 might appear slightly closer in this time series.

The Sylvia Grinnell Park thaw tube is located in a natural, wet, area with much greater rates of seasonal settlement (<11 cm/summer). This thaw tube provides a full summer of settlement measurements (Figure 7). Neither DInSAR data set follows the thaw tube measurements exactly, however, the CSK data seem to gradually catch up and by the end of the summer deliver displacement values comparable to the field measurements. The RADARSAT-2 results are more steady in their trend, but significantly under-estimate the total amount of displacement at the thaw tube. This under-estimation of the ground displacement in natural, often wet, terrain has been noted before in RADARSAT-2 DInSAR results (Short et al., 2014). It was suggested that surface ponding might be obscuring detection of settlement by the radar. Although it is not clear why CSK data should be less vulnerable to this effect.

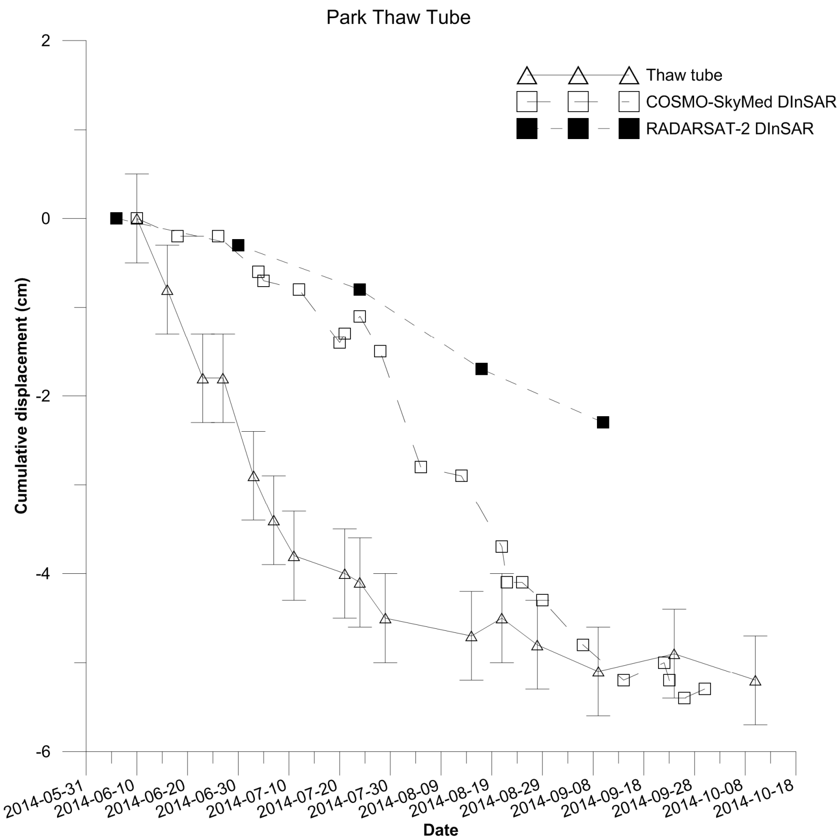
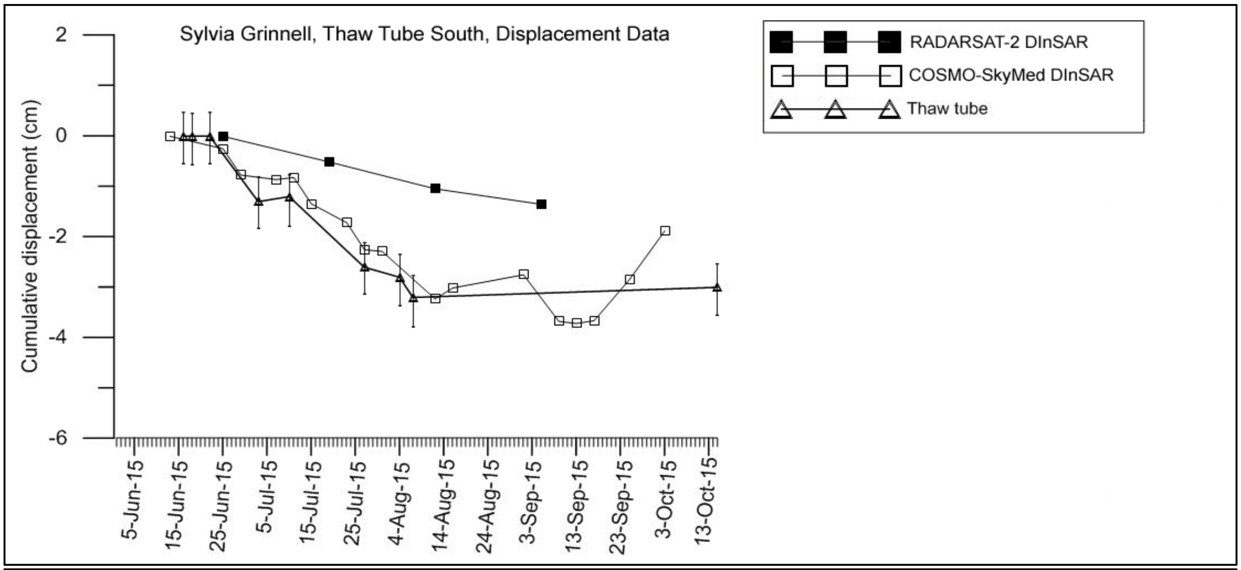
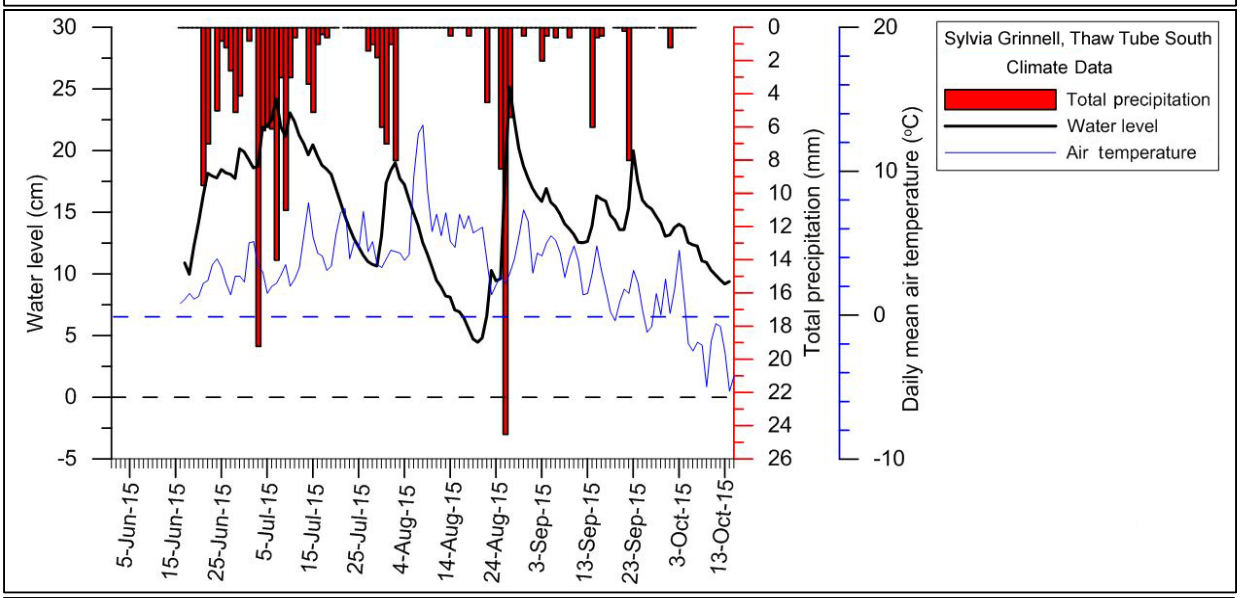


Figure 7. Sylvia Grinnell thaw tube measurements and CSK and RADARSAT-2 DInSAR results from summer 2014.

In the very short interval DInSAR data it is possible that residual atmospheric effect could produce an erroneous result in a pair; if this result affected the beginning of the time series, subsequent measurements may be more accurate, but the profile would be shifted. In contrast the RADARSAT-2 data have a longer interval and the displacement signal should be greater than any residual atmospheric noise, therefore the downward trend is more consistent, although for some reason, still under-estimated. With a dense data stack it is possible to identify stable targets and use these to detect and then correct for atmospheric effects. An experiment to do this on the CSK 2014 data was found to reduce variation and smooth the profile but it did not significantly alter the position of the profile, indicating that atmospheric contamination alone cannot account for the disagreement between the CSK DInSAR and the field measurements.

In 2015 the Airport thaw tube had been removed and a new tube was installed, also in Sylvia Grinnell Park but some distance to the north of the original tube (black triangles in Figures 4 and 5.) Figure 8 plots the displacement results for these sites. At the original Sylvia Grinnell thaw tube (south) (Figure 8:Upper) the CSK data show some agreement with the thaw tube settlement early in the season but there is some divergence later in the summer when we have sparse field observations. The RADARSAT-2 data are more steady in their downward trend, but as in 2014, under-estimate the amount of settlement. At the new Sylvia Grinnell thaw tube (north) (Figure 8:Lower) the RADARSAT-2 data track the field measurements closely while the CSK data experience much greater variability.


Sylvia Grinnell, Thaw Tube South, Displacement Data
RADARSAT-2 DInSAR
COSMO-SkyMed DInSAR
Thaw tube
Cumulative displacement (cm)
2
0
-2
-4
-6
5-Jun-15
15-Jun-15
25-Jun-15
5-Jul-15
15-Jul-15
25-Jul-15
4-Aug-15
14-Aug-15
24-Aug-15
3-Sep-15
13-Sep-15
23-Sep-15
3-Oct-15
13-Oct-15


Sylvia Grinnell, Thaw Tube South
Climate Data
Total precipitation
Water level
Air temperature
Water level (cm)
Total precipitation (mm)
Daily mean air temperature (°C)
30
25
20
15
10
5
0
-5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
20
10
0
-10
5-Jun-15
15-Jun-15
25-Jun-15
5-Jul-15
15-Jul-15
25-Jul-15
4-Aug-15
14-Aug-15
24-Aug-15
3-Sep-15
13-Sep-15
23-Sep-15
3-Oct-15
13-Oct-15

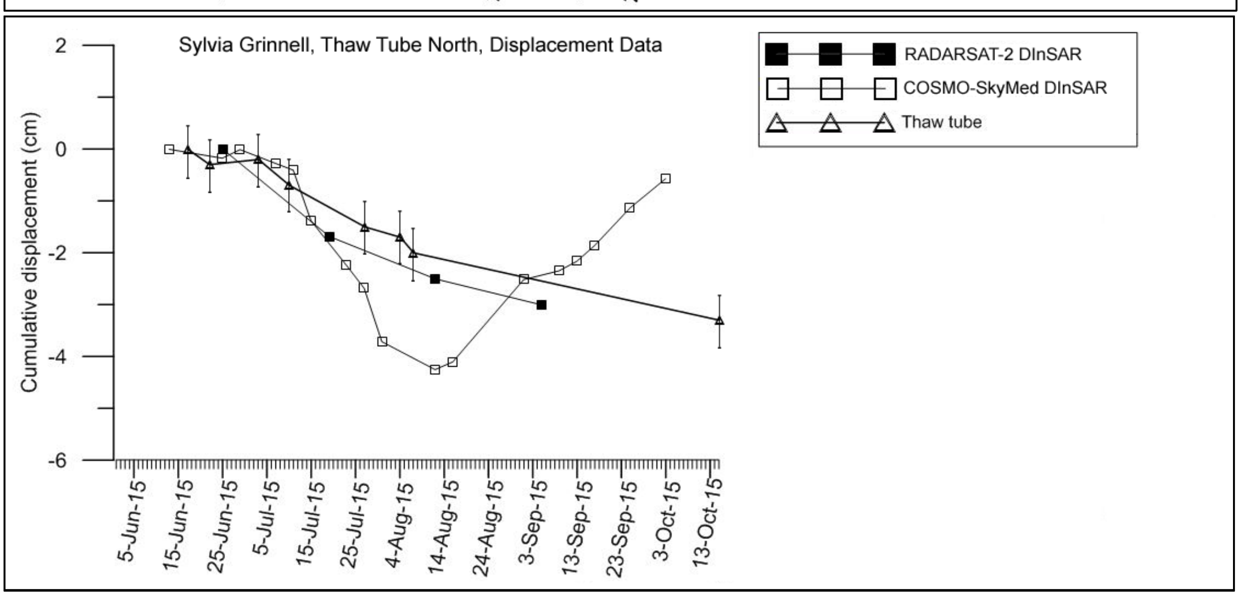

Sylvia Grinnell, Thaw Tube North, Displacement Data
RADARSAT-2 DInSAR
COSMO-SkyMed DInSAR
Thaw tube
Cumulative displacement (cm)
2
0
-2
-4
-6
5-Jun-15
15-Jun-15
25-Jun-15
5-Jul-15
15-Jul-15
25-Jul-15
4-Aug-15
14-Aug-15
24-Aug-15
3-Sep-15
13-Sep-15
23-Sep-15
3-Oct-15
13-Oct-15

Figure 8. Upper: 2015 displacement data from Sylvia Grinnell thaw tube south (see location in Figure 4), Middle: 2015 climate and water level data from Sylvia Grinnell south. Lower: 2015 displacement data from Sylvia Grinnell thaw tube north (see location in Figure 4).

An analysis of the relationship between settlement rates, temperature, precipitation and local water levels (Figure 8, Upper and Middle panels) did not yield clear conclusions. No relationship was apparent in the RADARSAT-2 data at all but some correlations were perhaps visible in the CSK data. In the CSK data the timing of precipitation events and rising water levels was cursorily, but not consistently and directly, associated with lower settlement rates or uplift, which might indicate masking of the settlement by flooding. RCM data will make it much easier to explore these relationships in the future.

It appears that the rapid revisit interval delivers advantages in cleaner displacement products and reduced noise levels as might be expected. It may also improve the accuracy of time series displacement measurements, however, this has not been unequivocally demonstrated in these comparisons with thaw tubes. An attempt to correct for residual atmospheric effects did not significantly improve the agreement of the DInSAR profiles with the thaw tubes, indicating that additional factors must be at play. Correlative efforts with precipitation, temperature and surface flooding factors were not conclusive, but suggest they might be influencing factors. Rapid revisit data will certainly enable a better analysis of these factors and it would be useful to understand these factors in order to improve data acquisition and processing strategies. In conclusion, RCM rapid revisit DInSAR stacks should provide excellent maps of average deformation rates and informative patterns, but time series plots of specific natural targets should be interpreted with caution as accuracy seems to vary with the nature of the site (sediments and drainage), the revisit interval of the SAR and the wavelength of the SAR.

5.2 Evaluating medium resolution data for permafrost terrain stability maps – Rankin Inlet

Figure 9 shows the DInSAR results from the RADARSAT-2 2015 Spotlight data stack over Rankin Inlet. The Spotlight data have a resolution of ~1 m. The blue areas indicate stable ground and include the bedrock area close to the community where the DInSAR reference point is located. A blue curvi-linear feature can be seen coming in from the top of the data coverage in the north east quadrant. This feature aligns with an esker on the topographic map. Eskers are comprised of sands and gravels which tend to drain well and be stable features in the terrain. This agrees well with the stable terrain signature (blue) in the Spotlight DInSAR result. The majority of the area has ground displacement in the low and moderate downward displacement categories (-1 to -7 cm) and only a few specific locations demonstrate the highest rates of settlement (-7 to -12 cm). Comparisons with surficial geology mapped by McMartin (2002) showed excellent alignment of DInSAR displacements with surficial geology units all across the scene, particularly in the shape and locations of stable bedrock outcrops (Short et al., 2016), giving confidence in the reliability of the DInSAR stability map. The 2016 Spotlight data stack lost an acquisition in June 2016 which compromised the quality of the stack, therefore only the 2015 results are included here.

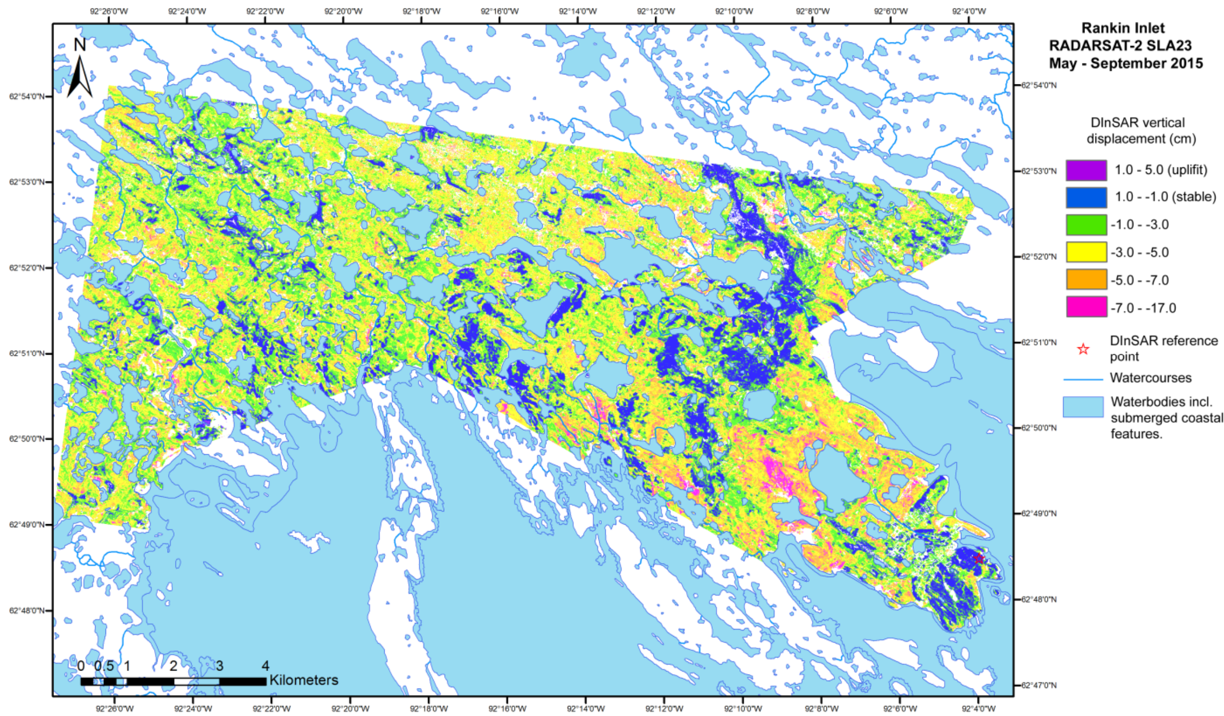


Figure 9. RADARSAT-2 Spotlight 23 DInSAR derived displacement for Rankin Inlet, summer 2015. Bedrock area near the community was used as the DInSAR reference point.

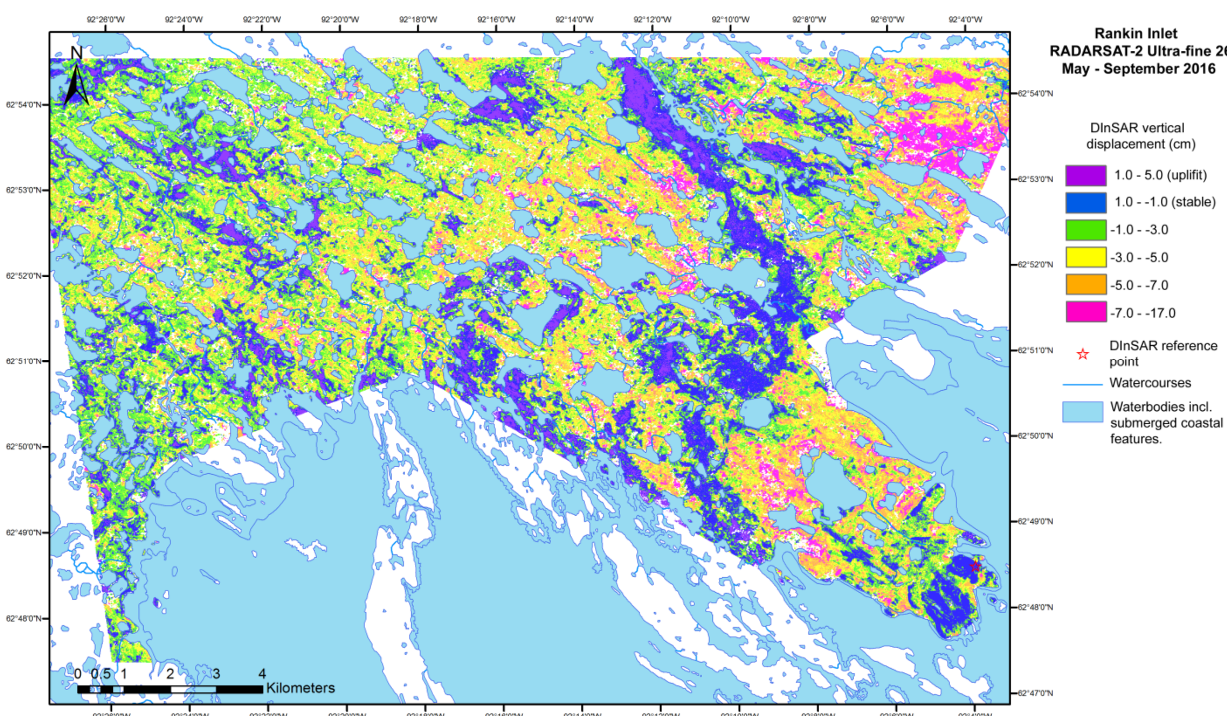


Figure 10. RADARSAT-2 Ultra-fine 26 DInSAR derived displacement in the Rankin Inlet region from summer 2016.

Figure 10 shows the DInSAR result using identical processing but with Ultra-fine RADARSAT-2 data (U26) as input. Note that the data coverage is larger in this data set. The resolution of the input Ultra-fine data is 3 m. In the vicinity of the community and near the reference point the patterns of displacement are generally similar to the Spotlight result. Local rock outcrops and the airport runway show similar levels of stability (blue) and local natural terrain areas show similar levels of displacement (pink/orange). However, there are pockets of local discrepancy, the promontory just north of the reference point is purple in the Ultra-fine result (uplift) but orange in the Spotlight result (subsidence). Whether this is a consequence of the different years of data, Spotlight were 2015 vs. Ultra-fine 2016 is not clear. That aside, patterns in the data sets diverge increasingly with distance away from the reference point in the Ultra-fine data. The stable esker feature exhibits increasing amounts of uplift (purple) further to the north, in the area of scene overlap as well as extending into the area that is only covered by the Ultra-fine data. To the west and north, many areas classified as stable in the Spotlight result (blue), and known to be stationary bedrock, become uplift (purple) in the Ultra-fine result. This may indicate an overall phase trend error, or a phase unwrapping error. An attempt to perform a simple trend detection and correction did not yield significant improvement, suggesting phase unwrap errors are more likely the source and these are more difficult to correct. The area of strong settlement (pink) in the north east corner of the Ultra-fine result is difficult to confirm because the Spotlight data do not cover that area. In other areas small anomalous patches of values do occur, but these are frequently at the edges of the processed scene, (for example, the purple patch along the north east image edge just below the aforementioned pink area). Scene edges are prone to phase unwrap errors and while these errors are more frequent in the lower resolution data, they are not purely a result of the resolution. In summary, the 3 m resolution data do provide information, but they are more prone to errors, particularly with distance away from the DInSAR reference point. It might be possible to add steps to the processing sequence to detect and correct for errors, but the success of that is uncertain.

Figure 11 shows an RADARSAT-2 Ultra-fine Wide DInSAR result (U18W2) from 2015. The result is much sparser and markedly different from the Spotlight and Ultra-fine products. Although the bedrock reference area is categorized as stable (blue) there is very little stable ground in the rest of the data coverage. Even the esker feature becomes green, categorized as low downward displacement, which from geomorphological knowledge is unlikely. Everything west of the bedrock reference location is subsiding to some degree, which would suggest either a phase unwrap error or a phase trend away from the reference point. While the sparser data could be interpolated to improve data coverage, with the errors in the input data, the resulting product would simply be erroneous. The resolution of the U18W2 data is the same as the Ultra-fine, 3 m, but in order to image a much larger scene area, a different downlink data compression strategy is used in the Wide mode. Ultra-fine Wide data are downlinked using 2-bit Block Adaptive Quantization (BAQ), whereas regular Ultra-fine and Spotlight data are downlinked using 3-bit BAQ. The 2-bit data compression strategy is known to reduce the quality of the recorded phase. The resulting introduction of phase noise into the radar products could have compromised the phase unwrapping steps and the reliability of the final displacement product, as well as reducing coherence levels which would have contributed to the sparse data coverage. While this serves as an interesting case study in understanding which RADARSAT-2 data modes to use in reliable interferometry, the RCM downlink mode is specified to be 4-bit BAQ (MDA, 2016) so hopefully this limitation will be avoided with the next mission.

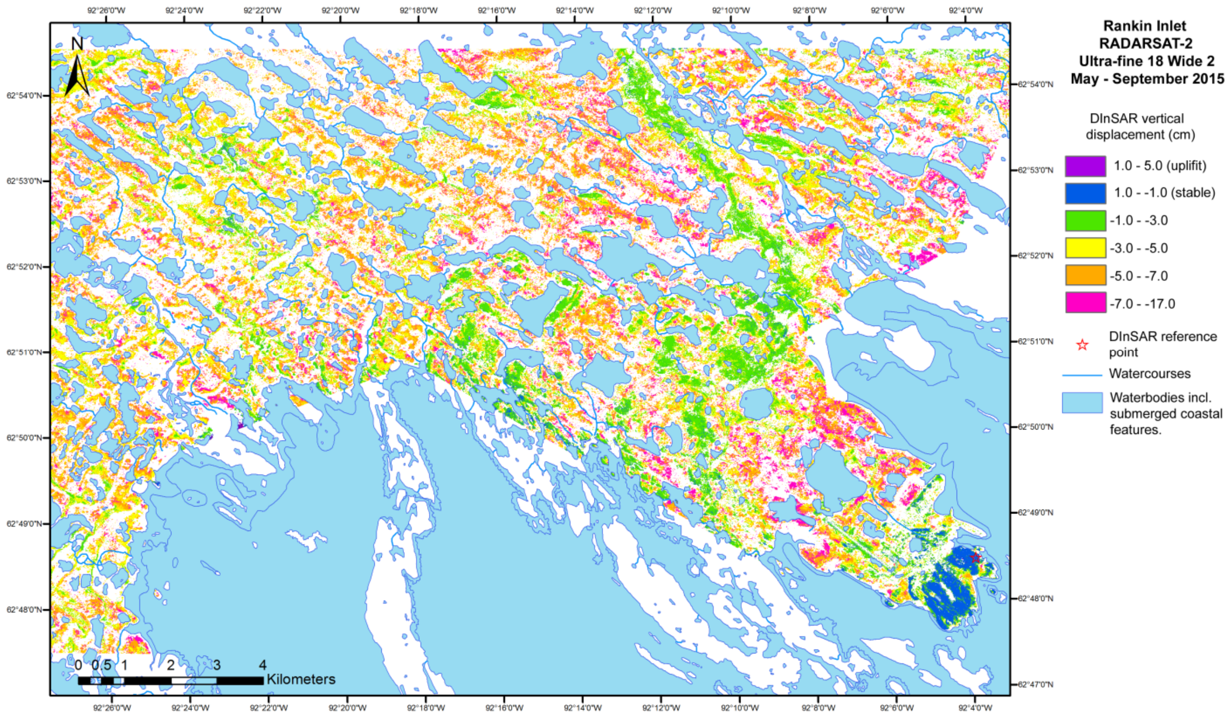


Figure 11. RADARSAT-2 Ultra-fine 18 Wide 2 DInSAR derived displacement around Rankin Inlet from summer 2015. Note the sparser result and slightly larger range of data values.

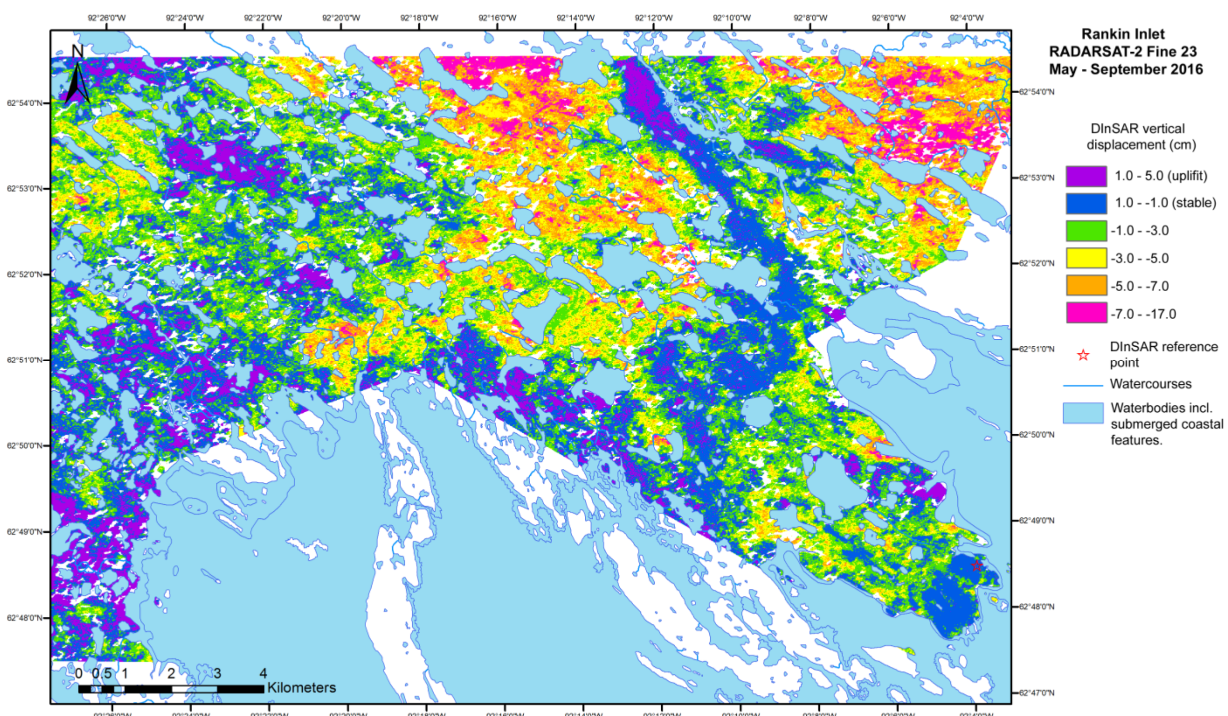


Figure 12. RADARSAT-2 Fine 23 DInSAR derived displacement for summer 2016 around Rankin Inlet. Note the widespread presence of purple (uplift areas) and disagreement in distribution of pink areas between this and other results.

The RADARSAT-2 Fine mode data product is shown in Figure 12. Fine mode resolution is 10 m. Once again the bedrock area near the community is well defined as stable, but an increasing area of the map now becomes purple, indicating areas of uplift. This uplift is visible over the esker feature and in many areas in the centre south and south west of the map. Unlike the Ultra-fine product, not all the purple areas are co-located with stable features in the Spotlight product. While the unstable pink area in the north east corner of the frame correlates reasonably with the Ultra-fine result, the pink area in the top centre of the Fine frame is in direct contrast with the stable /uplift features in the Ultra-fine product. These discrepancies cast significant doubt on the Fine mode results and suggest that significant errors have occurred in the phase unwrapping stage. The Fine mode data should not have been subject to any phase compression issues so the problems must be purely a consequence of the data resolution.

Lower resolution data while sometimes generally agreeing with the distribution of stable areas provide coarse results that are harder to validate. In addition, they are more vulnerable to phase trends and phase unwrapping errors with increasing distance from the reference point. Lower resolution data therefore require more quality control and additional processing to remove trends may be needed, although these may not always be successful. In general, there is more uncertainty and less confidence in the lower resolution data. The rapid revisit interval will increase coherence levels which may mitigate some of the disadvantages but it not clear to what extent. Data acquisition and delivery strategies of the RCM may potentially help to mitigate the problems (downlink modes and product formats) but it is also not clear to what extent.

6. Conclusions

The four day revisit interval of RCM can be expected to deliver better stack products, with better signal to noise ratios and cleaner, more complete and more reliable maps of seasonal terrain displacement, particularly when high resolution beam modes are used. Agreement with ground measurements is also likely to be closer, although these might still not be an exact match for reasons that are not yet fully understood. Understanding these reasons may help to improve data acquisition and processing strategies. The significant advantage of the four day repeat interval is not just better coherence and more accurate data in itself, but an increased number of observations, such that poor data sets (typically for atmospheric reasons) can be excluded, without noticeably compromising the duration or density of the stack.

The RCM Standard Coverage approach could be more problematic for the permafrost terrain stability application. While high resolution (1 m) Spotlight data consistently produce excellent results, the Ultra-fine (3 m resolution) and particularly the Fine mode (10 m resolution) were less reliable. Although a larger scene area is possible with the lower resolution data, errors increase away from the phase reference point and these errors are significant when detecting such small amounts and intricate patterns of displacement. Tentatively it appears that coarser resolution data miss the details of the natural terrain, this makes them vulnerable to phase unwrapping errors and impacts the accuracy of derived displacement products. It is not yet known to what extent the shortened revisit interval will compensate for the disadvantages of lower resolution data.

The possibility exists that if a Standard Coverage with medium resolution of 16 m is adopted, it will be of minimal value to the permafrost application. Even if the coherence and phase problems identified here can be overcome, this resolution will miss many details in the landscape and is well below the scale that infrastructure planners, managers and engineers require. Such comparatively low resolution data may be primarily useful for active layer modelling and long term, large scale environmental trend detection, such as has been demonstrated using stacks of ERS data by Liu et al. (2012). The question may well be posed, are we best served by another Sentinel-like medium resolution mission, or do the RADARSAT high resolution modes offer something uniquely valuable and immediately useful, access to which should, in some way, be preserved?

7. Acknowledgements

This work was funded by the Remote Sensing Science and the Climate Change Geoscience programs of Natural Resources Canada, by the Canada-Nunavut Geoscience Office and the Canadian Space Agency (contract 11SURCM001). RADARSAT-2 data were provided by MacDonald, Dettwiler and Associates under the RADARSAT-2 Government Data Allocation. Anne-Marie LeBlanc, Wendy Sladen and Greg Oldenborger of the Geological Survey of Canada are gratefully acknowledged for their permafrost knowledge and the field data collection. The Arctic College is also acknowledged for their field assistance at the Iqaluit site.

8. References

Allard, M., Doyon, J., Mathon-Dufour, V., LeBlanc, A.-M., L'Hérault, E., Mate, D., Oldenborger, G.A. and Sladen W.E., 2012. Surficial geology, Iqaluit, Nunavut. Geological Survey of Canada, Canadian Geoscience Map 64, scale 1:15,000. doi:10.4095/289503

Costantini, M., 1998. A novel phase unwrapping method based on network programming. *IEEE Transactions on Geoscience and Remote Sensing*, 36(3), 813-821, doi:10.1109/36.673674.

Goldstein, R. M. and Werner, C. L., 1998. Radar interferogram filtering for geophysical applications. *Geophysical Research Letters*, 25(21), 4035–4038.

Liu, L., Zhang, T. and Wahr, J., 2010. InSAR measurements of surface deformation over permafrost on the North Slope of Alaska. *Journal of Geophysical Research*, 115, F03023 doi:10.1029/2009JF001547.

Liu, L., Schaefer, K., Zhang, T. and Wahr, J., 2012. Estimating 1992-2000 average active layer thickness on the Alaskan North Slope from remotely sensed surface subsidence. *Journal of Geophysical Research*, 117, F01005, doi: 10.1029/2011JF002041.

Lyons, S. and Sandwell, D., 2003. Fault creep along the southern San Andreas from interferometric synthetic aperture radar, permanent scatterers and stacking. *Journal of Geophysical Research*, 108(B1), pp. 2047 doi:10.1029/2002JB001831

McMartin, I., 2002. Surficial geology, Rankin Inlet, Nunavut; Geological Survey of Canada, Open File 4116, scale 1:50,000. doi:10.4095/213219

MDA, 2016. RCM-SP-52-9092 Product Specification 1/7: January 26, 2016. MacDonald, Dettwiler and Associates, Richmond, B.C.

Short, N., Brisco, B., Budkewitsch, P. and Murnaghan, K., 2009. ALOS-PALSAR Interferometry for Permafrost Monitoring in Canada. Proceedings of the 3rd ALOS PI Symposium, November 9-13, 2009, Big Island, Hawaii. Alaska SAR Facility, Fairbanks, Alaska

Short, N., Brisco, B., Couture, N., Pollard, W., Murnaghan, K. and Budkewitsch, P., 2011. A comparison of TerraSAR-X, RADARSAT-2 and ALOS-PALSAR interferometry for monitoring permafrost environments, case study from Herschel Island, Canada. *Remote Sensing of Environment*, 115, 3491–3506, doi:10.1016/j.rse.2011.08.012.

Short, N., Brisco, B. and Murnaghan, K., 2012. Monitoring permafrost environments with InSAR and polarimetry, case studies from Canada. *Proceedings of IGARSS 2012, July 22-27, Munich, Germany*, IEEE, New York, NY.

Short, N., LeBlanc, A.-M., Sladen, W., Oldenborger, G., Mathon-Dufour, V. and Brisco, B., 2014. RADARSAT-2 D-InSAR for ground displacement in permafrost terrain, validation from Iqaluit Airport, Baffin Island, Canada. *Remote Sensing of Environment*. 141, p.40-51, doi:10.1016/j.rse.2013.10.016

Short, N., LeBlanc, A.-M. and Bellehumeur-Genier, O., 2016. Seasonal surface displacement derived from DInSAR, Rankin Inlet, Nunavut; Geological Survey of Canada, Canadian Geoscience Map 291 (preliminary), scale 1:35,000. doi:10.4095/298815

Strozzi, T., Grosse, G. and Streletskiy, D., 2012. SAR interferometry for surface deformation monitoring in permafrost areas in Alaska. *Proceedings of the Earth Observation and Cryospheric Science Conference*, *Frascatti, Italy, 13-16 November 2012,* ESA-ESRIN.

Werner, C., Wegmüller, U., Strozzi, T., & Wiesmann, A., 2000. GAMMA SAR and interferometric processing software. *Proceedings of ERS-Envisat Symposium, Gothenburg, 16-20 October, 2000.*

Wolfe, S. A., Short, N. H., Morse, P. D., Schwarz, S. H. and Stevens, C. W., 2014. Evaluation of RADARSAT-2 DInSAR Seasonal Surface Displacement in Discontinuous Permafrost Terrain, Yellowknife, Northwest Territories, Canada. *Canadian Journal of Remote Sensing*, 40:406–422, doi:10.1080/07038992.2014.1012836