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InSAR Monitoring of Arctic Landfast Sea Ice Deformation Using L-Band ALOS-2, C-Band Radarsat-2 and Sentinel-1

Zhaohua Chen *, Benoit Montpetit, Sarah Banks, Lori White, Amir Behnamian, Jason Duffe and Jon Pasher

Science and Technology Branch, Environment and Climate Change Canada, Ottawa, ON K1S 5B6, Canada; Benoit.Montpetit@ec.gc.ca (B.M.); Sarah.Banks@ec.gc.ca (S.B.); Lori.White@ec.gc.ca (L.W.); Amir.Behnamian@ec.gc.ca (A.B.); Jason.Duffe@ec.gc.ca (J.D.); jon.pasher@ec.gc.ca (J.P.)

* Correspondence: zhaohua.chen@ec.gc.ca

Abstract: Arctic amplification is accelerating changes in sea ice regimes in the Canadian Arctic with later freeze-up and earlier melt events, adversely affecting Arctic wildlife and communities that depend on the stability of sea ice conditions. To monitor both the rate and impact of such change, there is a need to accurately measure sea ice deformation, an important component for understanding ice motion and polar climate. The objective of this study is to determine the spatial-temporal pattern of deformation over landfast ice in the Arctic using time series SAR imagery. We present Interferometric Synthetic Aperture Radar (InSAR) monitoring of Arctic landfast sea ice deformation using C-band Radarsat-2, Sentinel-1 and L-band ALOS-2 in this paper. The small baseline subset (SBAS) approach was explored to process time series observations for retrieval of temporal deformation changes along a line-of-sight direction (LOS) over the winter. It was found that temporal and spatial patterns of deformation observed from different sensors were generally consistent. Horizontal and vertical deformations were also retrieved by a multi-dimensional SBAS technique using both ascending and descending Sentinel-1 observations. Results showed a horizontal deformation in the range of -95 – 85 cm, and vertical deformation in the range of -41 – 63 cm in Cambridge Bay, Nunavut, Canada during February–April 2019. High coherence over ice from C-band was maintained over a shorter time interval of acquisitions than L-band due to temporal decorrelation.

Keywords: InSAR; sea ice; SBAS; Arctic; deformation; ALOS-2; Sentinel-1; Radarsat-2



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1. Introduction

Arctic ice has been thinning and retreating due to global warming in recent years [1–4]. Given the vast sea ice extent and increasing commercial interest in the Arctic, it is important to map sea ice changes [5]. SAR satellite imagery is used routinely to identify and map sea ice changes due to its weather-independent capability [6]. Several C-band SAR satellites are also used to provide operational products of sea ice types, extent, and concentration due to the availability of a large amount of imagery [6–8]. With increasing data available from other SAR sensors, X- and L-band have also been found to provide complementary information for sea ice identification [9–12].

Recently, Interferometric Synthetic Aperture Radar (InSAR), a technique that measures the line-of-sight (LOS) motion of a target based on the phase differences between two SAR images, has been applied for monitoring sea ice stability and deformation [13–20]. The deformation is an important component of ice motion. It is attributed to thermal expansion and contraction or dynamic action (e.g., compression of the ice driven by winds, sea level tilt, currents, or internal ice stress) [16,17]. It is believed that most of the InSAR phase change over a coherent area are results of vertical or horizontal deformation of sea ice [13–15,18,20]. Aided with inverse modeling, InSAR may be used to determine ice deformation modes [16], rates [14,20], dynamics (e.g., associated stress and fracture patterns) [13,15,17,19,21], and topography [19,22].

InSAR measurement of sea ice deformation can be affected by both SAR sensor parameters (wavelength, polarization, incidence angles, and frequency of image acquisition) and target parameters (sea ice type, snow cover, salinity, sea ice thickness, roughness, and wetness). Interferometric information is useful only if the phase differences are from coherent areas. Coherence (value ranges from 0 to 1) is used to describe the quality of an interferogram that contains phase changes. Higher coherence values indicate higher phase correlation and less noise in the interferometric phase. Usually, targets that remain unchanged during the time interval of two image acquisitions have high coherence. On the other hand, low coherence values can be a result of temporal decorrelation, where there is little to no correlation among groups of pixels observed at the same location, through time. This can be a result of either significant motion occurring between acquisitions (measured relative to the radar wavelength) and/or due to a low temporal frequency of acquisitions. Notably, temporal decorrelation can be significant in areas dominated by floating ice, due to relatively quick horizontal movements because of wind/currents/waves, or wet ice due to melting [15–17,21]. Though generally speaking, for most natural surfaces, the longer the time interval between acquisitions is, the lower the coherence becomes. Loss of coherence is also dependent on the wavelength. Decorrelation is more pronounced at shorter wavelengths, such as X-band (2.5–4 cm), and C-band (4–8 cm), than longer wavelengths, such as L-band (15–30 cm). Many InSAR studies confirm improved coherence in L-band SAR data [14,16,23]. Wavelength also affects InSAR results because it impacts how incident microwaves interact with the snow/ice surface and ice volume [15,16,24]. Thus, the sensitivity of SAR to sea ice deformation is dependent on the penetration depth of a respective wavelength [12,25,26]. Longer wavelength microwaves can penetrate deeper than shorter wavelength microwaves [12]. InSAR coherence is generally higher and more stable over stationary landfast ice than drifting ice [16–19]. As a result, current efforts to monitor sea ice deformation using satellite data have therefore been mainly limited to landfast ice [13–15,20]. Landfast sea ice is an essential element of Arctic coastal sea ice systems, and its stability is critical for transportation and activities using ice as a platform [16].

Previous studies have been focusing on monitoring sea ice deformation along LOS direction from SAR observations using D-InSAR techniques [16–19,21,22]. InSAR derived deformation is the projection of the 3-D ice movement (containing north-south, west-east and up-down components) along the LOS direction, so it is 1D information. A recent study also indicated the possibility of resolving vertical and horizontal deformation from combined LOS measurements from a pair of ascending and a pair of descending images [20]. However, no information about temporal evolution of deformation is provided from D-InSAR products [27]. The temporal and spatial pattern of deformation may not be fully understood from the observation from a limited number of image pairs. To extract the information about temporal evolution of deformation, all available time series image observations must be linked through a proper approach. Then, components of deformation in different dimensions can be analyzed. Once the deformation is derived, validation of InSAR results is important. The validation of InSAR results can help improve the generation of products related to ice stability and deformation. However, it is difficult to verify InSAR derived ice deformation due to the cost associated with the installation of equipment for in situ measurements, the difficulty of accessing ice away from the shore, and limited spatial coverage of field measurements. With frequent SAR acquisitions, InSAR derived measurements may provide the information with increased spatial and temporal coverage that is not available from the in situ instrument. Assuming that fast ice does not move with the wind and sea current, and the deformation over coherent fast ice during the time interval of each two SAR acquisitions is linear, trends in detected changes from different sensors may be consistent and can be validated against each other. Therefore, it is important to investigate the InSAR performance on sea ice monitoring by evaluating if deformation trends from time series observations from different SAR systems are consistent by extracting vertical and horizontal information from time series LOS measurements.

To link time series SAR images and calculate the ice deformation over a certain period, the small baseline subset (SBAS) technique [27,28] may be applied. The SBAS method can connect interferograms spanning different time intervals and generate cumulative measurements of movements while minimizing effects from temporal decorrelation, atmosphere and topography [27–32]. Given deformation measurements from different looking directions, horizontal and vertical deformation may be resolved using multi-dimensional SBAS technique [30]. However, few studies have explored the temporal and spatial pattern of InSAR derived landfast ice deformation from different sensors. From this perspective, the objective of this study is to determine the spatial–temporal pattern of deformation over landfast ice in the Arctic using time series SAR imagery. We investigated InSAR potential for landfast sea ice deformation measurements from time series of SAR satellite images from different sensors in Cambridge Bay, Nunavut, Canada. In this paper, time series ice surface deformation from SAR sensors including L-band ALOS-2, C-band Radarsat-2 and Sentinel-1 were estimated and compared. The horizontal and vertical deformations were resolved using both ascending and descending Sentinel-1 images. We also investigated the change and difference in the coherence between L- and C-band SAR data over Arctic sea ice, and assessed how InSAR interferograms changed during the winter of 2018–2019.

2. Study Area and Data

Cambridge Bay is located on Victoria Island, Nunavut, Canada. It is directly connected to the Arctic Ocean and is partially covered by ice for most of the year. This study monitored the sea ice covering the Northwest Passage between Dease Strait and Queen Maud Gulf (Figure 1). During winter months, the entire area is covered by landfast first year ice (FYI), which varies in thickness depending on the time of year. Some multi-year ice (MYI) may flow from Victoria Strait to the east into the Queen Maud Gulf, but regional sea ice charts available from the Canadian Ice Service Data Archive (CISDA) [8] showed that the dominant ice type was FYI in the study area.

In order to understand the ice conditions in the study area, ice draft information by an upward looking Sonar Water Ice Profiler (SWIP), deployed by Ocean Networks Canada was studied. The ice profiler uses acoustics to measure the ice draft (depth of sea ice below the water), and is mounted on the ocean floor at a depth of 6 m near the Cambridge Bay dock [33] (Figure 1). A review of the observatory data of ice draft from previous years indicates that ice started to form on 15 October, 7 October, 1 October, and 8 October in 2016, 2017, 2018, and 2019, respectively. The ice melted on 29 June, 13 July, and 29 July in 2017, 2018, and 2019, respectively. The ice draft reached to a maximum of 1.62 m on 29 May 2017, 1.55 m on 11 June 2018, and 1.85 m on 11 June 2019, respectively (Figure 2). All images were acquired during December–May when ice conditions were stable and the effects from the seasonal melting and freezing of ice were minimum.

A total of six Radarsat-2 scenes of Fine Quad-Pol mode (FQ13) were collected during December 2018–May 2019 (Table 1 and Figure 1). Each image was acquired in the ascending orbit and was quad-polarized (HH, HV, VH, and VV). A total of 12 descending Sentinel-1 scenes of Interferometric Wide (IW) mode were collected during December 2018–April 2019, and nine ascending Sentinel-1 scenes of IW mode were collected during February–May 2019. The IW datasets were dual-polarized in both descending orbit (HH and HV) and ascending orbit (VV and VH). A total of six ALOS-2 scenes of HBQR mode were acquired during January–April 2019. The HBQR datasets of the high-sensitive mode were also acquired in the descending orbit and were quad-polarized (HH, HV, VH, and VV). A Canadian Digital Elevation Data (CDED) of 30 m spatial resolution was used to provide elevation information for image co-registration and topographic correction in InSAR processing. The elevations in the study area, including land and ocean, range between 0 and 90 m above mean sea level according to CDED.

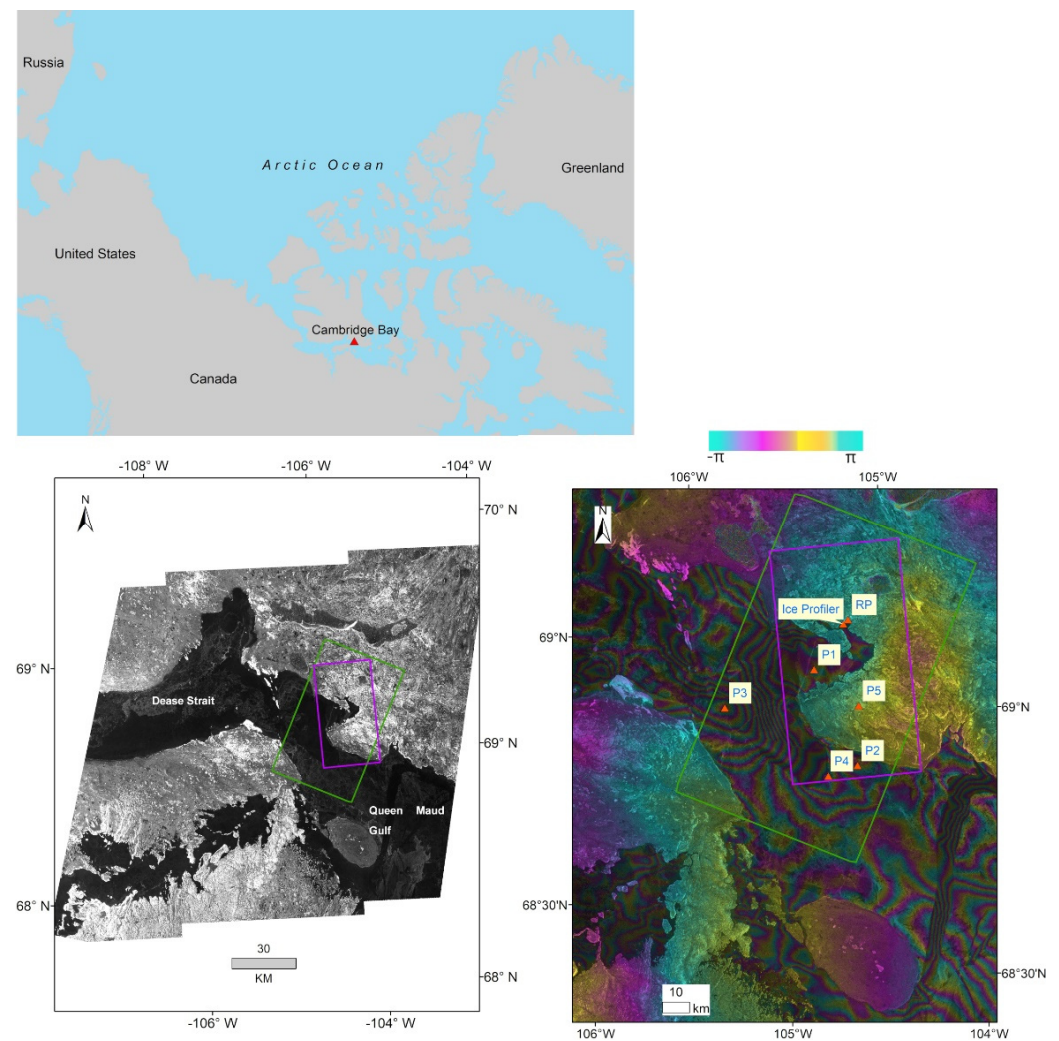


Figure 1. Upper left: map of study area showing the Arctic and Cambridge Bay location (the red triangle). Lower left: Cambridge Bay study area covered by ALOS-2 HBQR mode (green line) and Radarsat-2 FQ13 mode (purple line). The background is a Sentinel-1 image of IW mode acquired on 25 March 2019. Right: locations of Ice Profiler and InSAR measurements (RP, P1, P2, P3, P4, P5). The background is an example interferogram with clear fringes over the sea ice generated using Sentinel-1 IW mode of HH polarization acquired on 25 March 2019 and 6 April 2019.

Table 1. SAR data used for the InSAR analyses.

Sensor	Mode	Resolution (Range × Azimuth) (m)	Orbit Direction	Incidence Angles (Degrees)	Repeat Cycle (Days)	No. of Scenes Acquired
Radarsat-2	FQ13	16.5 × 14.9	Descending	33	24	6
ALOS-2	HBQR	4.3 × 5.1	Descending	39	14	6
Sentinel-1A	IW	2.7 × 22	Descending	33.4	12	12
Sentinel-1B	IW	2.7 × 22	Ascending	39	12	9

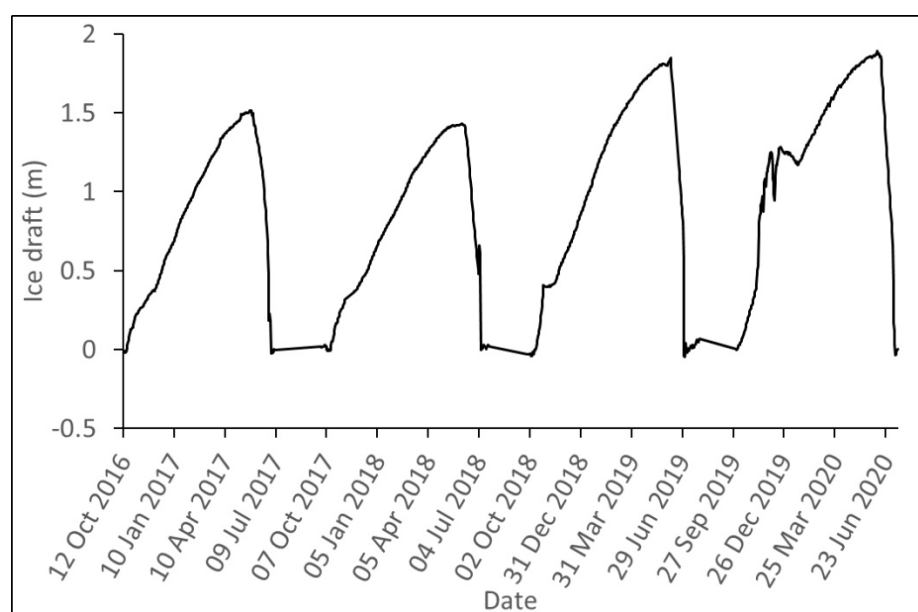


Figure 2. Ice draft changes from an ice profiler located at harbor of Cambridge Bay.

The location of the Arctic Station building in Cambridge Bay was chosen as a reference for InSAR measurements (RP). Four locations over the sea ice (P1, P2, P3, P4) were selected to investigate the ice deformation using InSAR. These locations represented different ice conditions, corresponding to water depths of 10 m deep near Cambridge Bay harbor (area close to ice profiler location) to more than 70 m deep in the strait [34]. P1 was located at an area with a water depth of 10–20 m, P2 at 40–50 m, P3 at 60–70 m, and P4 at 50–60 m (Figure 1). These locations were 5–10 km away from the shore and observed with consistent coherence from time series interferograms from both ALOS-2 and Sentinel-1 images. According to the record, ice thickness near our P1–P4 locations was at 185 ± 5 cm in 23–25 April 2014 and at 166 ± 16 cm in 17–19 May 2018 [35]. No location near the harbor was selected for InSAR monitoring because of its small size and proximity to land, making it easily affected by the resampling and filtering process. One location on the land near the sea was chosen for studying the movements of the land (P5).

3. Methods

In this study, InSAR monitoring of temporal and spatial pattern of ice deformation was completed in four steps. First, coherence variations over ice generated from data with different polarizations at different time intervals of acquisitions were assessed, and interferogram patterns were studied. Second, deformation along LOS was measured from each InSAR pair using D-InSAR techniques. Third, temporal evolution of deformation along LOS was calculated using SBAS analysis, temporal and spatial pattern of deformation changes observed from different sensors were compared. Fourth, horizontal and vertical deformation was resolved from multi-dimensional SBAS.

Traditional differential InSAR (D-InSAR) procedures including co-registration, interferogram generation and phase unwrapping were applied to each dataset with GAMMA software [36]. First, co-registration was applied to align and resample all images from one orbit (same sensor, polarization, and incidence angle) to a reference image. Multi-looking and resampling were applied to reduce speckle effects and to improve coherence estimation. Then, all possible InSAR pairs which were acquired within 100 days and perpendicular baseline less than 400 m were used to generate differential interferograms. Atmospheric correction was also applied to each interferogram based on the split-spectrum method, which separates the ionospheric and the non-dispersive phase terms using spectral sub-band images [37]. The phase noise of an interferogram was reduced using an adaptive phase filter [38], and then coherence and phase changes were estimated. The interferogram

was unwrapped to estimate the ice deformation along the LOS using the Minimum Cost Flow algorithm [39].

The accuracy of the InSAR derived deformation measurements depends on coherence. As interferometric coherence is a variable that contains the coherence magnitude and interferometric phase. The coherence magnitude can range from 0 to 1, and a high coherence value is associated with a good quality interferogram, which can be used to identify a fringe pattern that is related to sea ice deformation change. Therefore, only high coherent area was used to derive the deformation information from the phase information. The coherence values from HH, HV and VV polarizations from the same dataset such as ALOS-2 and Radarsat-2 were estimated to evaluate the performance of different polarizations on coherence over sea ice. By acquiring data with similar incidence angles from ALOS-2, Radarsat-2 and Sentinel-1, coherence differences in images at the same time were expected to be largely related to the wavelength.

The pattern and density of interferogram fringes describe the deformation type and rate, with frequent fringes indicating a higher density of phase changes and greater deformation. Generally, high fringe density indicates unstable ice conditions. Parallel fringes indicate strong lateral movement or compressions, and circular fringes are associated with vertical deformation [21]. In order to know if the ice deformation changes in Cambridge Bay could cause similar patterns to be observed from different sensors, fringe patterns from interferograms generated from sensors with the similar and different looking geometries over the same period were characterized.

Once interferograms were generated, a threshold of 0.4 was used to identify coherent and non-coherent areas. Coherence threshold of 0.4 was chosen to maintain the complete connected area in phase unwrapping and enough interferograms for the SBAS analysis. Only those areas which maintained high coherence (>0.4) were kept and correctly unwrapped for the next SBAS analysis. Assuming no significant movement at RP (Figure 1) during the study period, the deformation change was set to zero at RP. Then, a deformation map with respect to the reference pixel was computed to provide relevant information only to those pixels with high coherence. By exploiting all available SAR acquisitions, using interferograms generated from the D-InSAR technique with short spatial and temporal baselines, the SBAS technique was applied to calculate the temporal evolution of deformation along LOS. In the analysis, the Singular-Value Decomposition (SVD) algorithm was employed to achieve the minimum-norm least squares solution and to extract meaningful deformation information at any time interval. Finally, a time-series cumulative deformation representing the deformation changes from the first acquisition date was achieved. However, the traditional SBAS analysis only provides the time-series measurements along the LOS direction. To decompose LOS measurements into 3D ice movement components, multi-dimensional SBAS processing techniques were applied.

Multi-dimensional SBAS analysis integrates various InSAR datasets with overlapping temporal and spatial coverage for producing 2D/3D time-series of deformation. This technique requires time series LOS measurements from different imaging geometry [29,30,40]. Since current radar satellites such as ALOS-2, Radarsat-2 and Sentinel-1 are near-polar orbit, they are not sensitive to the displacement of the north-south direction, therefore no movement in north-south direction can be detected [20,29,30]. Assuming the north-south movement along the passage in Cambridge Bay was zero, and horizontal (west-east) and vertical (up-down) deformation were dominant motions, 2D measurements were decomposed from time series observations from both ascending and descending modes. The details of SBAS method and reconstruction of the horizontal and vertical deformation from LOS measurements using multi-dimensional SBAS have been detailed in previous research [27–30,41]. Theoretically, data from ascending and descending modes from different sensors can be integrated together to produce two-dimensional deformation [29]. However, previous studies indicated that L- and C-band had different penetration depth through ice [22,41], so the combined use of them may complicate the interpretation of results, therefore, they were not integrated for multi-dimensional SBAS analysis in this study.

No two-dimensional deformation analysis of L-band ALOS-2 data was conducted due to lack of ascending observations. Only C-band Sentinel-1 datasets with both ascending and descending observations were analyzed for horizontal and vertical information. In this analysis, negative values in vertical or horizontal InSAR measurements indicated downward or westward deformation, while positive values indicated uplift or eastward deformation.

4. Results

4.1. Observations of Coherence Change over Time

Coherence from C-band Radarsat-2 and Sentinel-1 and L-band ALOS-2 InSAR pairs were calculated for the period of December 2018–May 2019. Coherence from interferograms generated over short and long acquisition intervals was compared. In general, high coherence (>0.4) over sea ice started as early as in January from L-band, but only in mid-February from C-band. It was also found that coherence from L-band could be maintained over a longer period than C-band. Both the harbor of Cambridge Bay and Queen Maud Gulf area were coherent in most interferograms of HH and VV polarizations. Almost all ice areas remained coherent in the interferograms of 14 and 28-day intervals, while only 60% of this area remained coherent in the interferograms with 84-day interval. All ALOS-2 InSAR pairs from HH and VV polarizations with different time intervals from January to April 2019 produced high coherence at four ice locations (Table 2). Results over landfast ice in this study showed that both HH and VV polarizations returned strong backscatter which meant higher signal to noise ratio (SNR) and were advantageous over HV/VH in monitoring ice, thus were suitable for InSAR analysis over sea ice in the study area. The SBAS analysis of time series ALOS-2 interferograms generated from HH over stable coherent ice areas was conducted for cumulative deformation estimates.

Table 2. Comparison of coherence from L-band ALOS-2 image pairs generated from different polarizations with different acquisition intervals starting from 17 January 2019 (interferogram pairs were formed by cross-multiplying the image of 17 January 2019 with the subsequent acquisitions).

Coherence in HH Polarization				
Duration (Days)	P1	P2	P3	P4
14	0.78	0.88	0.89	0.91
28	0.96	0.99	0.97	0.62
42	0.78	0.90	0.98	0.87
70	0.81	0.92	0.94	0.47
84	0.80	0.82	0.92	0.19
Coherence in HV Polarization				
14	0.21	0.58	0.38	0.72
28	0.25	0.91	0.37	0.33
42	0.14	0.09	0.43	0.30
70	0.12	0.20	0.24	0.23
84	0.08	0.13	0.20	0.06
Coherence in VV Polarization				
14	0.84	0.95	0.97	0.93
28	0.97	0.98	0.99	0.75
42	0.89	0.78	1.00	0.77
70	0.92	0.95	0.98	0.41
84	0.95	0.79	0.98	0.17

Radarsat-2 FQ13 coverage was smaller than ALOS-2 and Sentinel-1 coverage, thus the sea ice area observed was limited to the Cambridge Bay harbor and nearby areas only. Coherence in interferograms of 48-day interval was generally very poor compared to those of 24-day interval. Coherence values from all interferograms generated using images acquired before mid-February were below 0.4. It was observed that only harbor areas were coherent from the interferograms of the pair of 22 December 2018–15 January 2019 and the pair of 15 January 2019–8 February 2019. Coherence was greatly improved in the interferograms generated using images acquired between March and mid-May. As such, most ice areas were coherent from the interferograms of the pair of 28 March 2019–21 April 2019 and the pair of 21 April 2019–15 May 2019. Coherence values from HH polarization at both P1 and P2 were >0.5 from the interferogram of 28 March 2019–21 April 2019 and >0.8 from 21 April 2019–15 May 2019. Similar to those results from L-band, coherence from VV polarization was comparable with HH, but very low from all interferograms from HV. SBAS analysis was not applied to Radarsat-2 data due to a limited number of high-quality interferograms.

Coherence from different polarizations from Sentinel-1 sensors were not compared because only dual-pol mode data were available for this study. Coherence from different polarizations from Sentinel-1 sensors were expected to have similar results as those from Radarsat-2 because both are from C-bands. However, interferograms from Sentinel-1 data acquired after mid-February generally had improved coherence compared to Radarsat-2 due to shorter repeat-pass acquisition duration (12 days vs. 24 days). As such, InSAR pairs from Sentinel-1 acquired during mid-February–April were used for the SBAS analysis.

Results from all sensors, especially C-band, showed that the coherence over ice was high (>0.4) near or along the coast where ice attached to the coastline or sea floor, then decreased toward the open ocean. Based on our observations, it was found that coherence over sea ice were strongly affected by temporal baselines. Therefore, a small temporal baseline subset was preferred for ice deformation estimates. Interferograms from C-band with longer time intervals (>12 days) may not be suitable for ice deformation monitoring due to low coherence, in particular, interferograms from Radarsat-2 data.

4.2. Characterizing InSAR Interferograms

Interferograms generated using all ALOS-2 images of HH polarization acquired from January to April had good quality due to high coherence (Figure 3). ALOS-2 interferogram of 17–31 January 2019 showed mainly narrow and parallel fringe patterns (Figure 3A). Wider fringes appeared in the smooth ice area (darker color ice surface including locations of P1, P3, and ice profiler) starting from 14 February, and similar interferogram patterns maintained until April 11 (Figure 3B–E). From the interferogram of 28 March–11 April, two obvious circular fringe patterns representing opposite deformation direction appeared in this area (Figure 3F).

Only two image pairs from HH polarization of Radarsat-2 acquired during March–May produced high quality interferograms (Figure 4). Radarsat-2 interferograms only revealed the pattern covering the Cambridge Bay and coastal region due to the small coverage, and thus were not compared with that from the ALOS-2 and Sentinel-1 images. There were more fringes from Radarsat-2 (Figure 4A) than ALOS-2 (Figure 3F) in March–April because of shorter wavelength used. Sentinel-1 images of HH polarization acquired during mid-February–April and images of VV polarization acquired during mid-February–May produced high quality interferograms (Figures 5 and 6). Interferograms from Sentinel images also showed patterns of large circular fringes formed in February–April (Figures 5D and 6D). It was found that interferograms from ALOS-2, Sentinel-1A and Sentinel-1B showed similar fringe patterns of deformation at P3 and P4.

Parallel and dense fringes generated over most ice area before February in this study indicated that strong lateral deformation was dominant, while a rapid ice growth was observed from the ice draft measurements during the same period (Figure 2). Circular and less dense fringes were observed over some ice areas during March–April also indicating

that vertical deformation (uplift or depression) increased. The existence of both parallel and circular fringes observed from four sensors after mid-February indicated that there were both lateral/horizontal and vertical motion over the landfast ice in the study area.

Among the four locations over ice, P1 and P3 were located at the smooth ice surface (appeared dark and homogeneous on SAR image), P2 on the rough ice surface (appeared bright and patchy on SAR image) and P4 was located at the transition between the smooth ice surface and rough ice surface. The fringe patterns before March on two sides of P4 were different (Figures 3–6), which also suggested that interferogram phase changes were caused by different strains on two sides. A north-south oriented ice ridge (the bright linear feature on SAR image) identified near P1 has resulted in a fringe discontinuity.

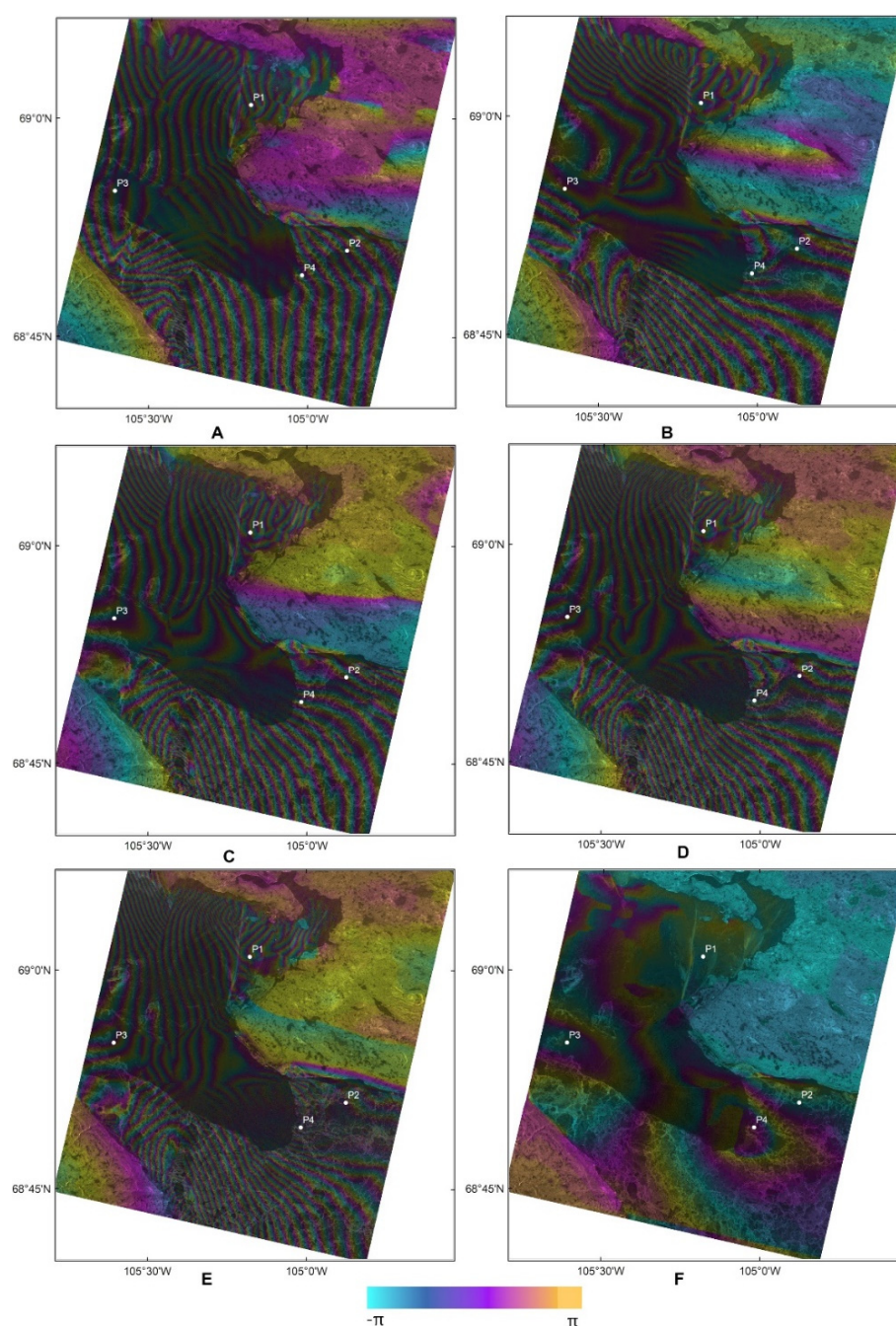


Figure 3. ALOS-2 interferograms from HH polarization (A): 17–31 January, (B): 17 January–14 February, (C): 17 January–28 February, (D): 17 January–28 March, (E): 17 January–11 April, (F): 28 March–11 April. One cycle of color ($-\pi$ to π) representing 12 cm in range change.

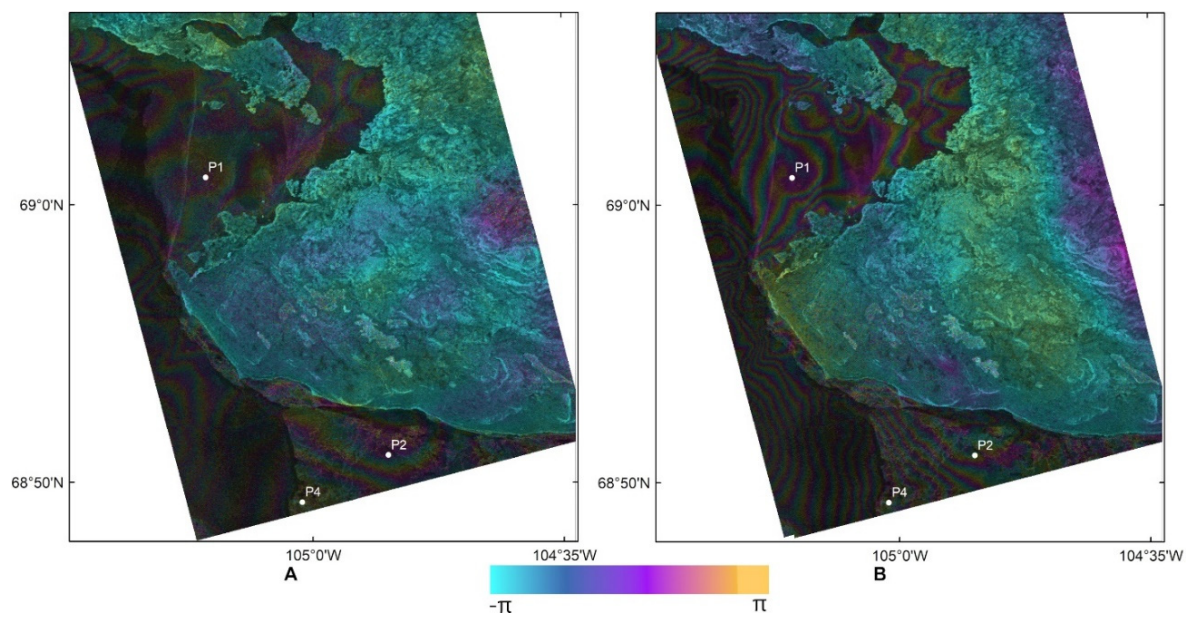


Figure 4. Radarsat-2 FQ13 interferograms of HH polarization. (A): 28 March–21 April, (B): 21 April–15 May. One cycle of color ($-\pi$ to π) representing 2.8 cm in range change.

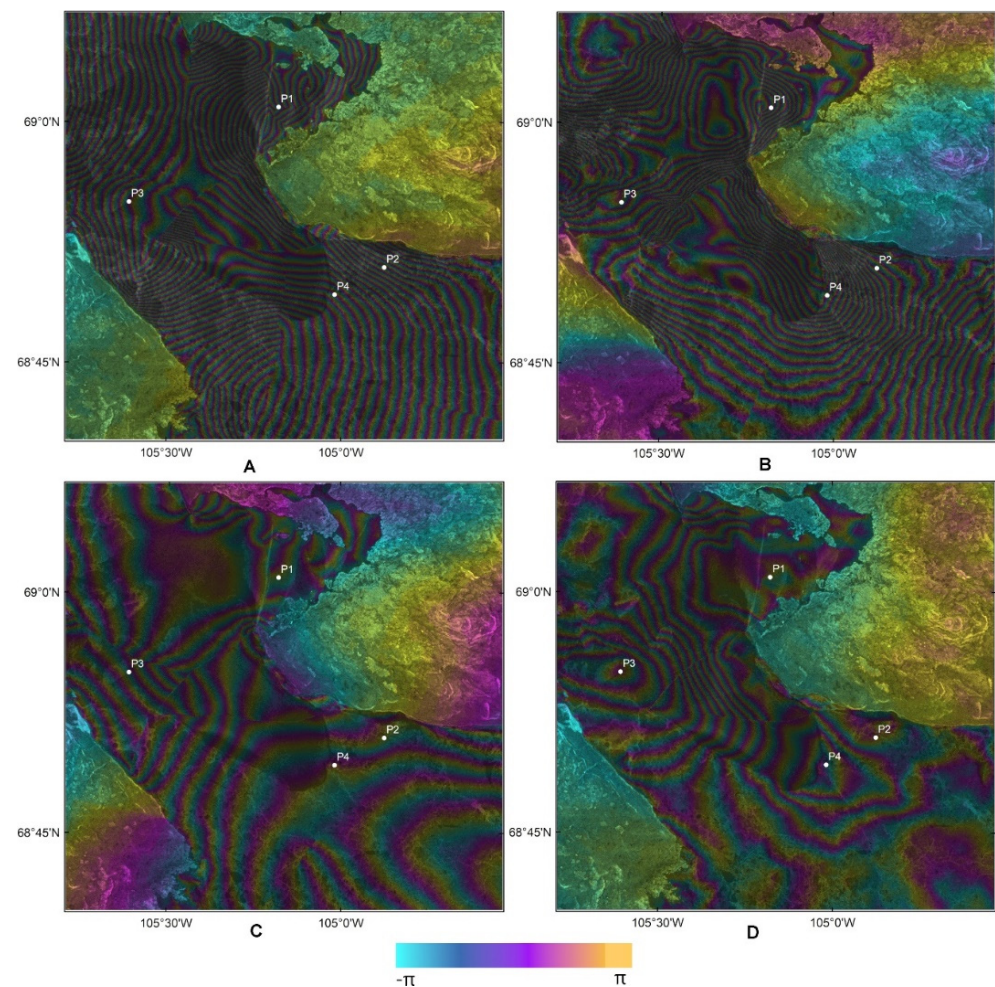


Figure 5. Interferograms from descending Sentinel-1A of HH polarization (A): 17 February–1 March, (B): 1–13 March, (C): 13–25 March, (D): 25 March–6 April. One cycle of color ($-\pi$ to π) representing 2.8 cm in range change.

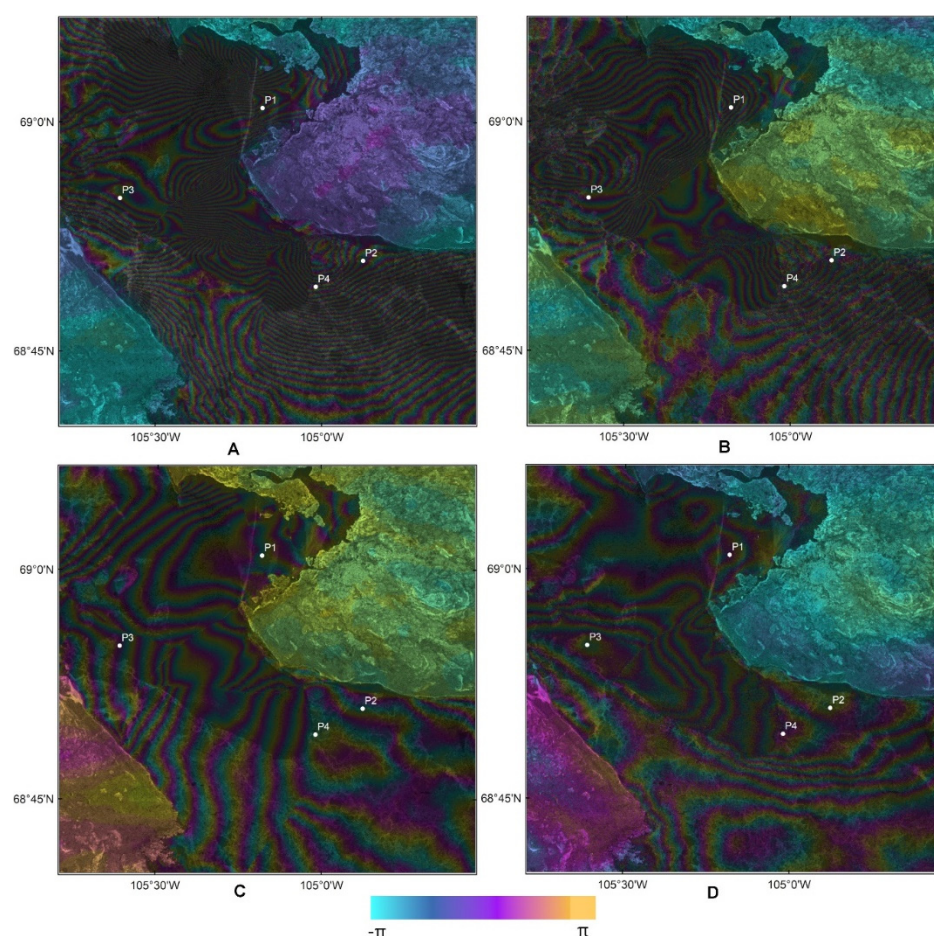


Figure 6. Interferograms from ascending Sentinel-1B of VV polarization (A): 9–21 February, (B): 21 February–5 March, (C): 5–17 March, (D): 10–22 April. One cycle of color ($-\pi$ to π) representing 2.8 cm in range change.

4.3. InSAR Deformation Results and Validation

The cumulative estimates of deformation in the LOS direction from SBAS analyses of both ALOS-2 and Sentinel-1 at four locations were compared and validated against each other due to lack of field measurements. All InSAR measurements were calibrated as changes relative to the RP. Land location P5 experienced only a slight fluctuation of movement in all interferograms during the study period (Figures 7–9). It is apparent that the ice draft growth was monotonic during January–May (Figure 2), the LOS displacement at P3 measured from ALOS-2, Sentinel-1A and Sentinel-1B generally also indicated such monotonic motion (Figures 7–9). The change in deformation trend at P1, P2 and P4 from ALOS-2 also agreed with Sentinel-1A and suggested that the deformation mode may have changed starting from mid-February (Figures 7 and 8).

It is expected that different SAR sensors with the similar looking geometry would produce comparable observation results over the same period. Any differences in results from the descending ALOS-2 and Sentinel-1A with slightly different incidence angles (39 degrees vs. 33.4 degrees) mainly resulted from the different wavelengths they used (L-band vs. C-band). It was found that both sensors agreed well in deformation trends (e.g., P2 and P3 moving toward the sensor, P1 and P4 moving away from the sensor), but differed in LOS magnitudes of deformation by 2.2 cm, 4.2 cm, 43.8 cm and 20.4 cm at P1–P4 locations, respectively (Table 3). On the other hand, any differences in results from the Sentinel-1A and Sentinel-1B datasets were mainly caused by different looking geometries (descending vs. ascending) and polarizations they used (HH vs. VV). The same movement would show opposite direction when monitored from the opposite looking geometry. Our results

from these two sensors also indicated that deformation trends agreed at P1, P3 and P4 locations, but measurements differed by 3.6 cm, 9.4 cm, and 39.2 cm, respectively (Table 3). As the interferogram phase was only sensitive to the projection of a 3D motion into the LOS direction, different deformation trends detected by Sentinel-1A and Sentinel-1B at P2 was probably associated with the ice tilt direction. It is believed that the large horizontal deformation at both P1 and P4 were associated with the significant lateral motion near ice ridge and transition surface. No cumulative estimates were available from Radarsat-2 due to a lack of sufficient interferograms for SBAS analysis, instead, differential estimates of deformation at P1 and P2 only were provided (Table 4). The deformation trend detected at those two locations by Radarsat-2 based on D-InSAR techniques (Table 4) was consistent to that observed from ascending Sentinel-1B data. However, the deformation magnitude detected from Radarsat-2 was much less than that from Sentinel-1 due to different time intervals and datasets. In general, the results indicated that magnitudes of LOS deformation varied in different looking directions and different wavelengths. However, the deformation trends measured by different sensors generally agreed with each other.

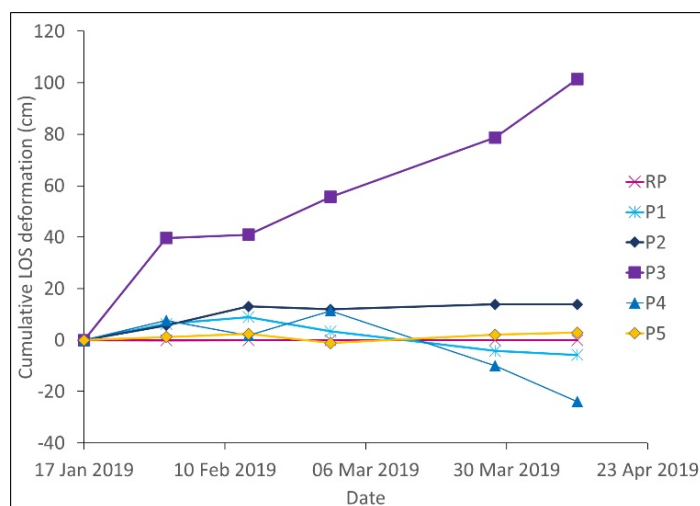


Figure 7. ALOS-2 (Descending mode) InSAR cumulative LOS deformation (relative deformation between the first date and subsequent dates) from HH polarization (+ for movement toward sensor, – for movement away from sensor).

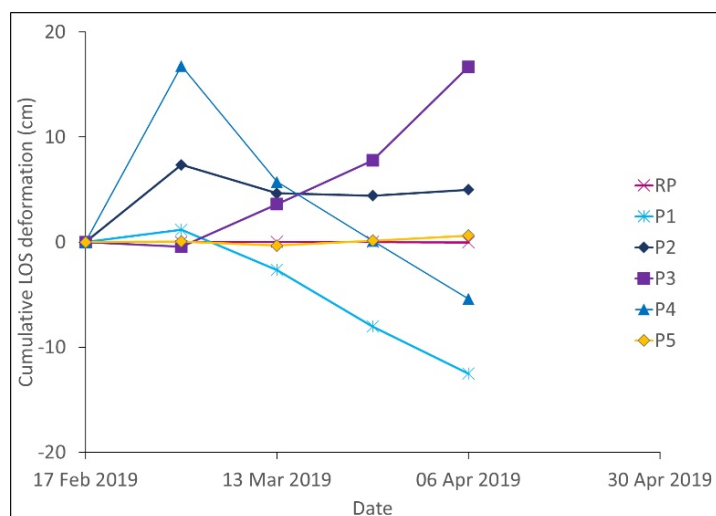


Figure 8. Sentinel-1A (Descending mode) InSAR cumulative LOS deformation (relative deformation between the first date and subsequent dates) from HH polarization (+ for movement toward sensor, – for movement away from sensor).

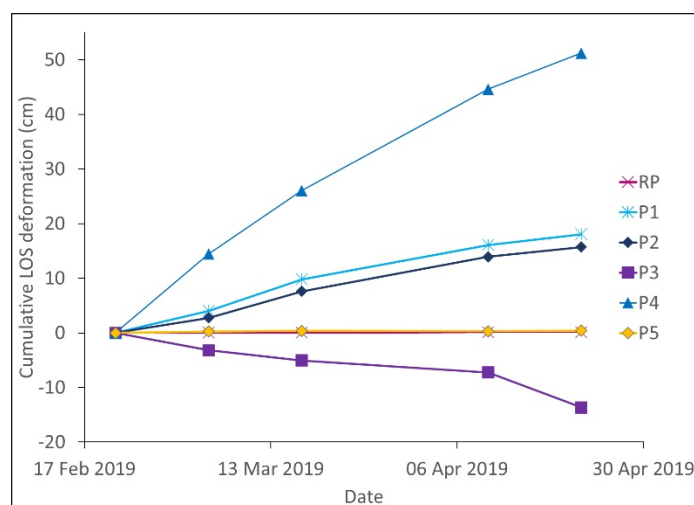


Figure 9. Sentinel-1B (Ascending mode) InSAR cumulative LOS deformation (relative deformation between the first date and subsequent dates) from VV polarization (+ for movement toward sensor, – for movement away from sensor).

Table 3. Cumulative InSAR measurements from SBAS and multi-dimensional SBAS analyses (LOS direction: + for movement toward sensor, – for movement away from sensor; horizontal direction: + for eastward movement, – for westward movement; vertical direction: + for upward movement, – for downward movement).

Direction	Time Period	P1	P2	P3	P4
LOS (descending ALOS-2)	14 February–11 April	–5.7 cm	13.9 cm	101.5 cm	–23.9 cm
LOS (descending Sentinel-1A)	17 February–6 April	–12.5 cm	5 cm	16.7 cm	–5.4 cm
LOS (ascending Sentinel-1B)	21 February–10 April	18.1 cm	15.7 cm	–13.6 cm	51.2 cm
Horizontal (combined Sentinel-1A and Sentinel-1B)	21 February–6 April	–28.9 cm	–14.8 cm	21.7 cm	–61.8 cm
Vertical (combined Sentinel-1A and Sentinel-1B)	21 February–6 April	–0.7 cm	6.6 cm	9.4 cm	9.7 cm

Table 4. D-InSAR measurements at location P1 and P2 using ascending Radarsat-2 FQ13.

Date	InSAR (P1)	InSAR (P2)
28 March–21 April 2019	5 cm	–1 cm
21 April–15 May 2019	8 cm	–2 cm

Temporal coverage of Sentinel-1A (17 February–6 April) data was different from that of Sentinel-1B (21 February–22 April, respectively). Therefore, multi-dimensional SBAS analyses of these two datasets could only cover their overlap period (21 February–6 April). Horizontal and vertical deformation maps were generated from multi-dimensional SBAS analyses (Figures 10 and 11). The final deformation in the east–west and up–down directions for the period 21 February–6 April in the study area is provided in Figures 10F and 11F, respectively. A horizontal deformation in the range of –95–85 cm, and a vertical deformation in the range of –41–63 cm were detected in the landfast area for the 44 days period. Generally, the area near the coastline experienced less deformation than the center channel area. Among the four locations, P1, P2 and P4 experienced westward horizontal movement at a total of 28.9 cm, 14.8 cm, and 61.8 cm, respectively, and P3 experienced a total of 21.7 cm eastward movement (Figure 12 and Table 3). P2, P3 and P4 experienced a 6.6 cm, 9.4 cm and 9.7 cm upward deformation, respectively, and P1 experienced a total of 0.7 cm downward deformation (Figure 13 and Table 3).

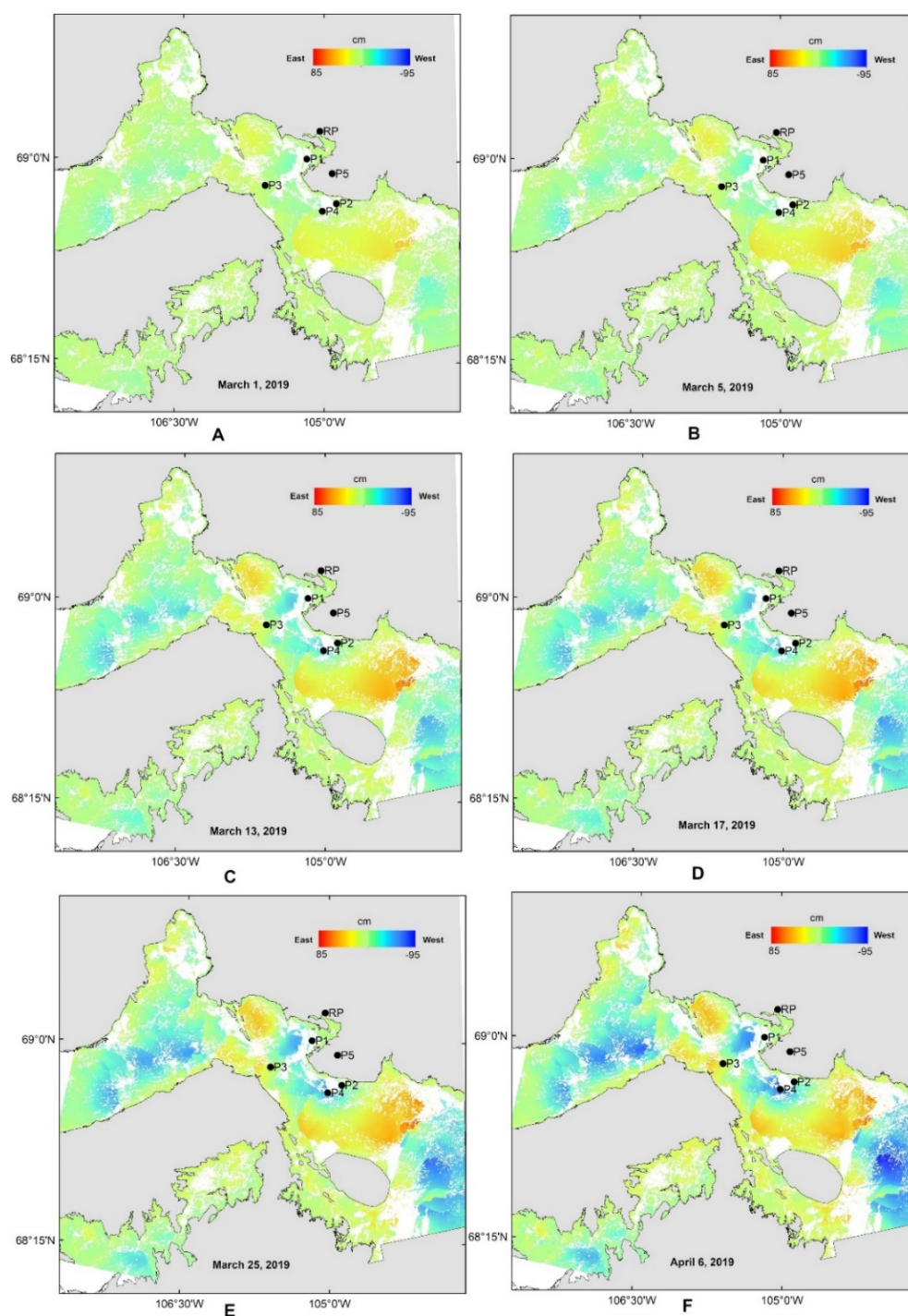


Figure 10. (A–F) Horizontal deformation from Sentinel-1A and B modes (+ for west–east movement, – for east–west movement). The grey and white color represent land and no measurements, respectively.

In the processing, phase unwrapping errors have been largely corrected or reduced by selecting datasets with small temporal and spatial baselines in the SBAS procedure, and other phase contributions have been properly removed with preprocessing (atmospheric correction, orbital trends). Two factors including DEM and reference location may have contributed to the uncertainty of cumulative measurements. The topographic residues may remain in the results due to the available CDED dem with a coarse spatial resolution (30 m) and low vertical accuracy (5 m). In the process, we used a building as reference to calibrate

all InSAR measurements. This may not be absolutely accurate since we assumed no ground motion at this reference location. We think that the differences in measurements from different sensors were mainly caused by the looking geometry, polarization and wavelength of observation data used. However, SAR condition at different SAR observation dates may have changed, which may also have contributed to changes in intensity, coherence, and measurement in InSAR analysis. The difference in measurements caused by polarization was not evaluated.

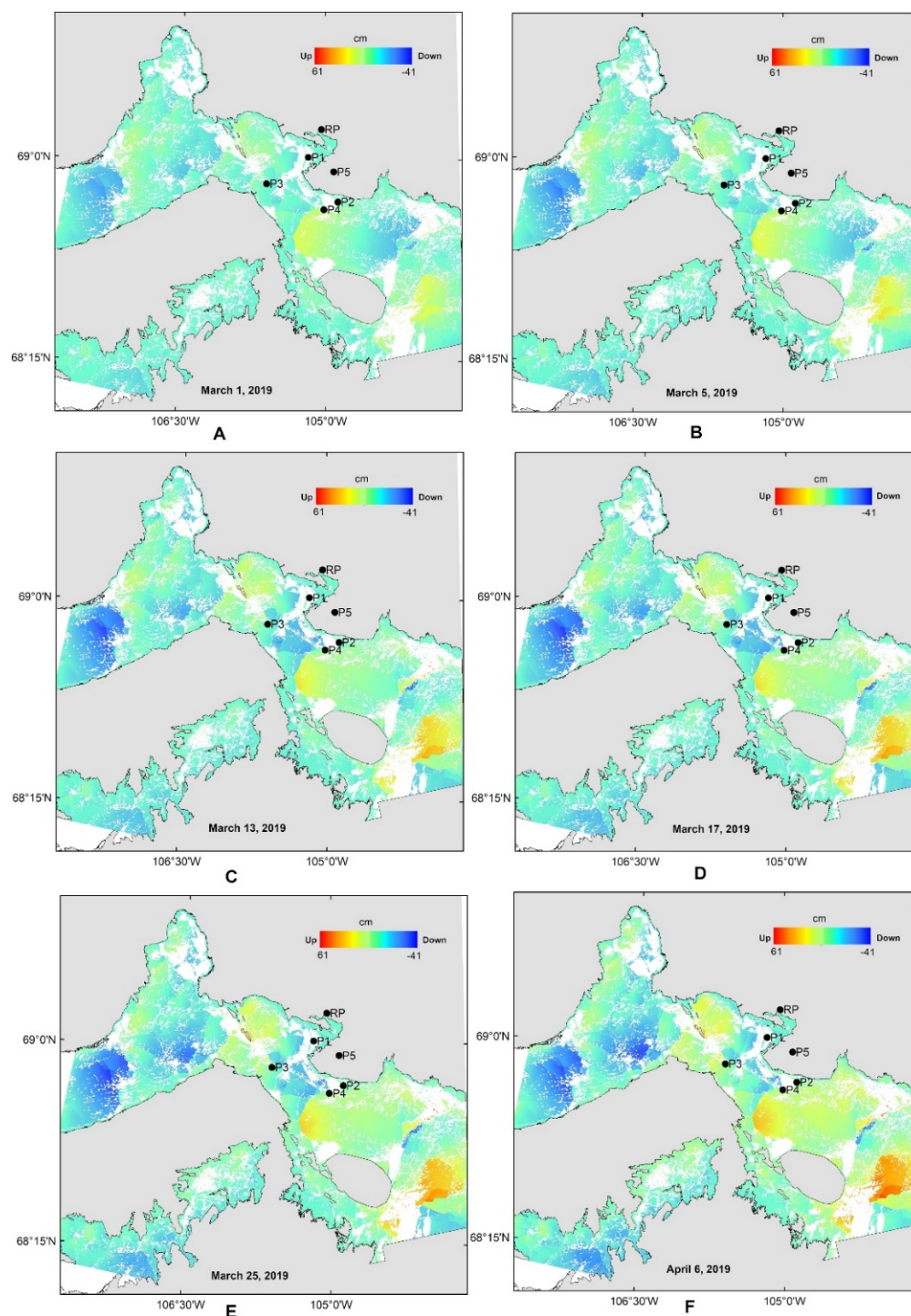


Figure 11. (A–F) Vertical deformation from Sentinel-1A and B modes (+ for upward movement, – for the downward movement). The grey and white color represent land and no measurements, respectively.

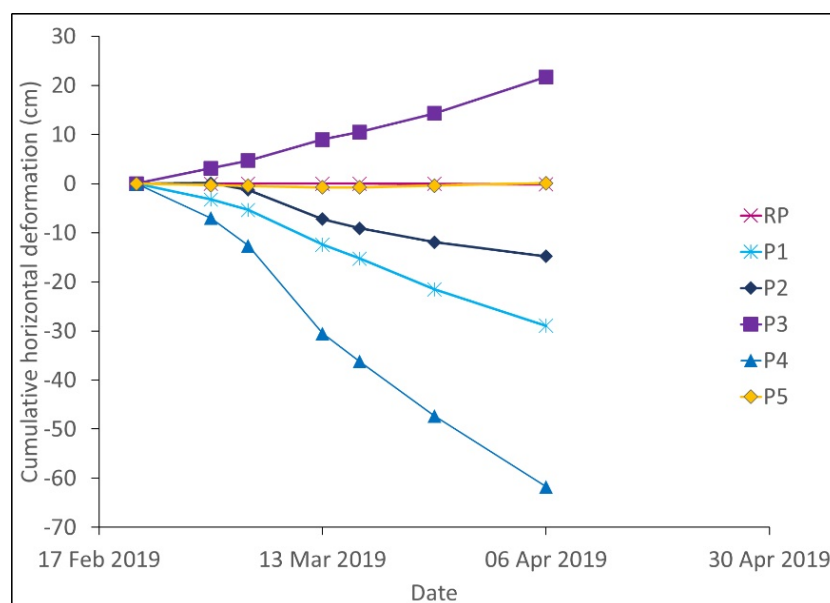


Figure 12. Sentinel-1 InSAR cumulative horizontal deformation (west-east) from combined analyses of ascending (VV polarization) and descending (HH polarization) observations. + for eastward deformation, – for westward deformation.

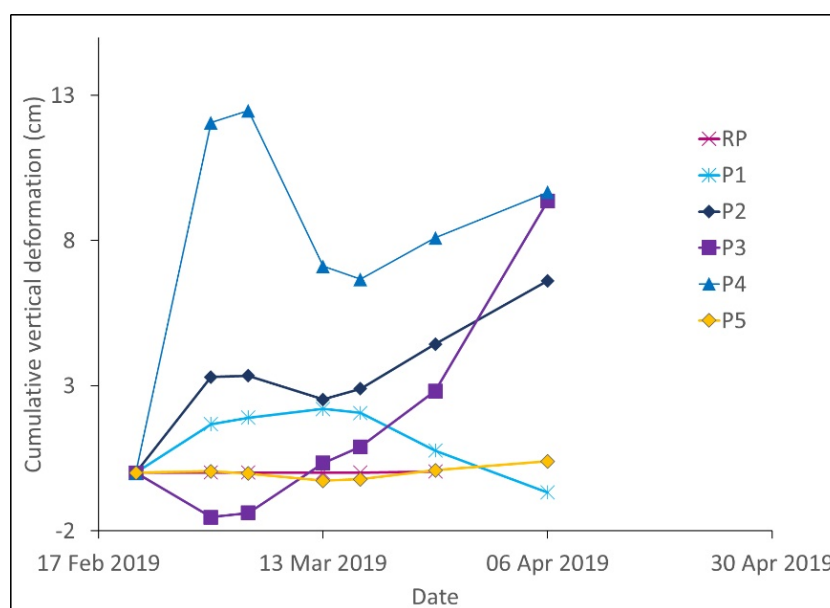


Figure 13. Sentinel-1 InSAR cumulative vertical deformation (up-down) from combined analyses of ascending (VV polarization) and descending (HH polarization) observations. + for upward deformation, – for downward deformation.

4.4. Comparison with Previous Studies

InSAR techniques have been used to investigate the landfast ice deformation over the Baltic Sea and Alaska Beaufort Sea, though with a very different set-up from this study. Marbouti, M. et al. [17] determined a displacement in a range of -10 – 30 cm in LOS direction using a pair of Sentinel-1A images (6 and 18 February 2015) in a region of Bothnia Bay, Baltic Sea. Wang et al. [20] detected a west-east deformation in a range of -44 – 26 cm and up-down -3 – 16 cm using four Sentinel scenes to form two interferometric pairs (2 and 14 February 2018; 4 and 16 February 2018) in that same region. Dammann et al. [16] measured a maximum vertical displacement of 90 cm using a pair of L-band ALOS-1 images

(31 March and 16 May 2010) near Foggy Island Bay, Alaska. In another study conducted in Beaufort Sea, Dammann et al. [18] evaluated the performance of a InSAR pair from X-band TerraSAR images (12–14 February) and L-band ALOS-1 (21 March and 6 May 2010). The InSAR derived LOS displacement was compared with DGPS-derived differential motion based on the field data collected from Northstar Island, Alaska. The in situ measurement reported an east–west deformation in a range of -20 – 160 cm, and a vertical deformation in the range of -20 – 70 cm during 7 January–14 April 2015. Dammann et al. [18] concluded that InSAR derived deformation was slightly higher than DGPS measurements with an error of up to roughly 25%.

To our knowledge, no InSAR studies have been conducted over Cambridge Bay. Different from the previous InSAR studies, which only used a pair or two pairs of InSAR images, more SAR acquisitions were used for generating time series interferograms to study the deformation patterns. For example, six L-band ALOS images allowed us to generate 15 interferograms at different intervals (14–84 days), and to show the evolution of the deformation over ice. High coherent interferograms generated from 12 Sentinel-1 images also demonstrated the possibility for establishing the long-term monitoring of deformation over a large coverage in the Arctic using the C-band data. With the integration of the Sentinel-1 ascending and descending orbits data, the deformation trend and spatial-temporal patterns have been further analyzed. We not only obtained the displacement value of fast ice in LOS direction over a long period, but also calculated the evolution of vertical and horizontal deformations using the SBAS method, which were not available in previous studies. Although the ice deformation modes and magnitudes in those previously studied regions may be different from Cambridge Bay due to different deformation mechanisms and ice conditions, results from this study were in a comparable range with those reported before. For example, a maximum of 142 cm LOS displacement was observed during 17 January–11 April using ALOS-2 images. A horizontal deformation in the range of -95 – 85 cm, and a vertical deformation in the range of -41 – 63 cm were detected during 21 February–6 April using integrated Sentinel-1A and Sentinel-1B images. Many interferograms used in the deformation analysis in this study also ensured to minimize the phase unwrapping errors, atmospheric effects and topographic phase residues, thus provided more accurate deformation measurements comparing with the previous studies.

5. Discussion

For estimation of the deformation over drifting ice, there exists an ice tracking algorithm which identifies patterns of radar backscatter in sequential SAR images and estimates the spatial displacement of those patterns between the images [42]. However, such pattern-based method may not be applicable over immobile landfast ice due to unchangeable patterns between images. Consistently higher coherence over landfast ice than drifting ice has prompted exploration of InSAR techniques for landfast deformation studies. Different from previous InSAR studies, time series deformation along LOS, vertical and horizontal deformation components were estimated using SBAS analysis in this study. InSAR performance over landfast ice was evaluated using L-band ALOS-2, and C-band Radarsat-2 and Sentinel-1 data. InSAR derived deformation from different datasets were compared. Comparison was made between different sensors, but with the same looking geometry and between the similar sensors but a different looking geometry. Results showed that spatial and temporal patterns from different datasets were generally consistent with each other, though magnitudes of LOS deformation varied in different looking directions and different wavelengths.

Variations of InSAR measurements may be attributed to the fact that backscatter can be affected by factors including sensor characteristics (e.g., wavelength, repeat cycle, viewing geometry and polarization), and ice surface conditions (e.g., snow cover, salinity, surface height, thickness, roughness, stability, types, air bubble concentration, and deformation) [10,22,43,44] in addition to coherence loss from temporal decorrelation. The tide plays a very important role in the ice distribution, thickness, and concentration in the

Arctic. The sea water in the study region is dominated by the Atlantic tidal forcing and partially influenced by the Arctic tidal forcing. The Atlantic tides from the east and Arctic tides from the west drive the formation of leads and polynyas and mobilizing of the sea ice in the channel of the study area. Although the tidal amplitude reached its minimum of the year in March at about 9 cm due to the total landfast ice blockage in the channel [45], we think the large variation of east–west deformation detected in this study was associated with the tidal forcing.

The accuracy of InSAR measurements depends on the coherence and quality of interferograms. Therefore, coherence changes and interferogram patterns were also evaluated during the winter season. Temporal decorrelation over ice was more obvious from C-band Radarsat-2 and Sentinel-1 than L-band ALOS-2 in this study. Coherence from C-band only lasted within a 24-day interval compared to L-band ALOS-2 data, which maintained coherence over an 84-day interval. This may be attributed by the penetration depth of different wavelengths. With a larger penetration depth, the SAR signal at L-band is more sensitive to internal ice structures, which are more stable in landfast sea ice compared to C-band, which is more sensitive to its surface structures [41]. The improved coherence over ice in L-band SAR data has been reported before [14,16]. Similar observations of lower correlation over sea ice from C- and X- band compared to L-band were also reported in other studies [14,18]. It was found that the coherence from all sensors over ice was high along the coast, where ice is attached to the coastline or sea floor, then decreased toward the open ocean. InSAR coherence was generally poor from the images acquired before January. Poor coherence over ice before January was probably caused by unstable ice condition and mobile ice. Low coherence from images acquired at early winter season was reported by other studies before. Dammann et al. [21] found that coherence from Sentinel-1 InSAR pairs acquired before March was low because of unstable ice conditions when mapping Arctic bottomfast ice in Alaska. The coherence was lost when the magnitude of movement was large relative to the SAR wavelength and the shift between two acquisitions changed the ice surface, consequently, interferograms could not be generated using C-band data before January.

All images acquired after February produced consistent high coherence over ice when ice draft growth reached a certain depth, for example, 1.5 m thick at the location of ice profiler close to Cambridge Bay. The appearance of circular and less dense fringes on interferograms acquired during March–April was believed to be related to more stable ice condition and thick ice in the study area. Decreasing fringe density as ice thickens over the winter has been reported before [16], while others have also used fringe densities in general to study the stability conditions of ice [16,21]. In those studies, dense fringe areas were considered unstable. One of the differences between ALOS-2 and Sentinel-1 observations was the quality of interferograms. In this study, ALOS-2 interferograms from January were considered reliable for deformation analysis given high coherence though with dense parallel fringes, however, Sentinel-1 interferograms were only reliable starting from mid-February. Sentinel-1 InSAR interferograms before February showed parallel and dense fringes. The results from this study showed that the harbor area (near the area where the ice profiler was located) had near-zero phase change during the winter because of the ice anchored to the floor, which distinguished it from the area further into the strait. Therefore, the relationship between sea ice thickness and InSAR measurement could not be studied directly.

InSAR coherence from both HH polarization has been proven to be higher and more stable than other polarizations (i.e., VV, HV, VH) in studying targets with low backscatter such as permafrost [26,40] and some wetland types [32]. However, results over landfast ice in this study showed that high coherence could be produced from both HH and VV polarization and was thus advantageous over other polarizations (HV/VH) in monitoring sea ice. Throughout most of the winter, sea ice near Cambridge Bay is covered by snow. Snow thickness on the FYI may affect microwave interaction [35], which affects the accuracy of measurement. In this study, we did not study such an effect. Given the fact that the snow

depth in Cambridge Bay only reached a maximum of 8 cm during April–May [46], and the snow thickness variation on landfast ice is within 1 cm in Cambridge Bay area [35], it is not likely to have had a significant influence on backscatter and coherence, especially at C- and L-band backscatter due to their penetration capacity [24,43]. The snow thickness variation may not directly affect the spatial–temporal pattern of deformation. Sea ice roughness and ice type may affect the coherence. It was noticed that the rough ice area (P2) in the study area exhibited high coherence from HH, VV and HV polarizations over a long time period. The influence of polarization, wavelength, sea ice type and roughness on coherence and InSAR measurement may be studied further when field data is available in the future.

Our analysis is strictly based on time series interferograms, which limits the ability to fully evaluate InSAR potential since results were not validated with field measurements. Validation with field measurements would strengthen InSAR application in the Arctic research, but this study is here kept to InSAR analysis using imagery from multi-sensors to focus on method development and understanding of spatial–temporal pattern in sea ice deformation. It is suggested that the future deployment of a Differential Global Positioning System (DGPS) in the field to record the ice motion at various locations. Three-dimensional displacements collected by DGPS can be used to validate the deformation components. The Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) mission launched in 2018 provides surface height measurements from laser pulses bouncing off the ice surface. With close to 1–2 cm accuracy and a 91-day orbit cycle, ICESat-2 can be very important for studying ice conditions in the Arctic [47,48]. It provides an opportunity to complement InSAR in monitoring elevational changes. However, there was no repeating acquisition during our study period. Comparison of sea ice surface height changes derived from ICESat-2 and deformation derived from InSAR may be conducted in the future.

Landfast ice can often grow and cover a large area [21]. Large areas with high coherence and various fringe density in the study area also demonstrated the possibility of ice extent and stability mapping using InSAR, which has been applied elsewhere [14,19,21]. Field measurements of sea ice in the Arctic Ocean can be logistically expensive and challenging. Consistent temporal and spatial patterns of change detected over landfast ice from different SAR observations may be an important indicator for evaluating the InSAR potential for providing accurate sea ice change information over a large area. The pattern and density of fringes may be used to infer different stages of landfast ice. With the approach demonstrated in this paper, observations from frequent SAR acquisitions showed promise for more reliable and consistent results. Studying ice stability and deformation using InSAR may be a viable solution for the Arctic communities.

6. Conclusions

In this paper, the performance of InSAR to observe landfast ice deformation in the Arctic Ocean was investigated using C-band Radarsat-2 and Sentinel-1 and L-band ALOS-2 satellite data. The spatial–temporal pattern of deformation was determined using SBAS approach. Comparison of results indicated that InSAR derived deformation pattern from different datasets were generally consistent. Two dimensional horizontal and vertical deformation were resolved from LOS deformation by combining both ascending and descending data using multi-dimensional SBAS analysis. A horizontal deformation in the range of −95–85 cm and a vertical deformation in the range of −41–63 cm were observed in Cambridge Bay during February–April 2019. Results from this study demonstrated that the trend of deformation from one dataset may be validated using other datasets. L-band ALOS-2 achieved higher coherence over longer acquisition intervals compared to C-band Radarsat-2 and Sentinel-1 due to temporal decorrelation. The challenge of temporal coherence loss could be resolved with higher temporal revisits of new modern SAR sensors such as the RADARSAT Constellation Mission launched in June of 2019. Results indicated that InSAR data with a high temporal revisit showed promise for investigating the Arctic sea ice deformation over a large area.

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