Speckle Tracking for 2-Dimensional Ice Motion Studies in Polar Regions: Influence of the Ionosphere.

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Abstract

Speckle tracking can be used to estimate glacial ice motion in coherent pairs of SAR images. The technique is particularly appropriate when either the ice motion or temporal separation of the data acquisitions are large. Examples of ice motion derived from speckle tracking analysis of the NASA/CSA Antarctic Mapping Mission interferometric data are shown.

In this, and in earlier work, it has been shown that occasionally streaks are observed in interferograms acquired at polar latitudes. Usually the effect is observed in the coherence, but associated modulation has also been observed in the phase. This affect arises from a km scale modulation in the optimum azimuth registration. The streaks in azimuth registration, or azimuth 'shift', could not be caused by terrain motion and were treated previously as an 'artifact' of unknown origin. We present evidence that the effect is caused by small scale ionospheric disturbances associated with polar auroral regions. We propose that imagery of the azimuth shift streaks is related to a 2-dimensional 'shadow' of the along-track gradient of the integrated electron density.

Introduction

Goldstein *et al*., (1993) clearly demonstrated the value of InSAR for mapping glacial ice motion, but also indicated that use of differential phase could be limited by temporal decorrelation. Results from the RADARSAT Antarctic Mapping Program (RAMP) have shown that phase coherence can be maintained over 24 days in Antarctica, particularly when studying the motion of ice in lower snow accumulation areas away from the coast. However, the relatively large temporal separation of the repeat coverage for current and future satellites (RADARSAT; 24 days, ERS-2; 35 days, ENVISAT; 35 days, ALOS; 46 days), coupled with the large speeds that can occur in outlet glaciers and ice streams, complicate the analysis of differential phase for radial ice motion for coastal or high speed regions. In these circumstances, a speckle tracking technique can yield 2 dimensional ice motion, albeit with reduced accuracy in the range direction.

Examples of results obtained from the RAMP with the speckle tracking technique are shown for ice motion in two areas in Antarctica. In one area, the Filchner Ice Shelf, traditional interferometry relying on unwrapped phase for radial motion would have been impossible because of patchy coherence and the possibility of fringe aliassing due to occasional very high fringe rate. The later arises due to the 24 day acquisition separation. The strength of speckle tracking for ice motion lies in the ability to estimate 2-dimensional motion from one pair of images, and the fact that there is no need for phase analysis. Of course, some of the same limitations apply to this technique as with the analysis of differential phase: uncertainties in the satellite orbits and resulting baselines, DEM errors, tidal motion of floating ice, and even errors arising from propagation effects. In addition, the speckle tracking technique will also have errors in the fine registration of the image chips used for the speckle tracking. As these errors tend to be random, averaging can reduce this contribution to the overall error in ice motion.

Azimuth streaks have previously been identified as a problem in polar interferometry (Jezek and Rignot, 1994, Joughin *et al*., 1996), and are a problem for speckle tracking. The streaks are related to a modulation in the optimum fine scale azimuth registration that could not be related to topography or ice motion. No explanation of the streaks has been given previously and it was generally assumed to be some kind of an artifact. Direct and indirect evidence for a link to ionospheric disturbances are presented here.

Speckle Tracking Method

Estimation of 2 dimensional ice motion has been used by Thiel *et al*., (1996) and by Michel and Rignot, (1999). In our application of the technique, Gray *et al*., (1998), the following straightforward processing steps are performed:

- Doppler centroid parameters are estimated for pairs of images along the desired pass.
- Processing of the complex image pairs is done with an appropriate azimuth bandwidth and Doppler centroid model such that further filtering is not necessary for optimum coherence.
- Fine registration of image chips is done by cross-correlation of detected image chips. The image chip size is variable but is normally optimal in the range 0.5 to 1 km. To avoid any loss of resolution when detecting the complex imagery the I,Q data is upsampled by a factor of 2 in both the range and azimuth directions. As this is done with a sin(x)/x resampler, the spectra of the complex data is shifted to zero Doppler prior to the resampling.
- Estimates of range and azimuth shift are obtained by finding the peak in an upsampled 2 dimensional cross correlation function. As the upsampling is done by a factor 20, the resolution of individual estimates of shift is 1/40 of the azimuth or range sampling. Poor points can be rejected when the correlation coefficient falls below a certain level.
- Data from the relevant part of the DEM (Bamber and Bindschadler, 1995, Liu *et al*., 1999) is interpolated up to an appropriate resolution (~ 100m) and converted into an earth centred, earth fixed (rotating) frame.
- By using a model for the satellite position, the DEM data can be mapped into the SAR slant range frame and useful parameters assigned to the centres of each of the image chips used for azimuth and range shift. These are; cell latitude and longitude, incidence angle at the ice surface, SAR look angle at the satellite, ellipsoid height, radar range, range and azimuth surface slopes, azimuth direction, and the difference in ranges to the 2 satellite tracks (parallel baseline). Note that the later is variable in both range and azimuth and implicitly accounts for topographic and orbit variations.
- Because of the limited accuracy of the orbit data, it is necessary to use in-scene control to calibrate the derived velocities. By using areas of known velocity, preferably zero, refinements to the baseline model are possible.
- The ice velocity is calculated using the straightforward, previously published, equations (Gray *et al*. 1998).

Application of speckle tracking to AMM RADARSAT data of Antarctica

Knowledge of ice motion on a large scale is essential to undertanding the mass balance of Antarctica. Our current lack of knowledge compounds the problem of forecasting future global sea level rise. Understanding current ice dynamics is also essential to any discussion of ice sheet stability, for example the West Antarctic ice Sheet (WAIS), see Bindschadler *et al.* 1998. Two examples of results from the application of speckle tracking are given below.

Tributaries of West Antarctic Ice Streams

A combination of speckle tracking and phase interferometry has been used to monitor the catchment area for the ice streams feeding the WAIS (Joughin *et al*., 1999). The WAIS is of particular interest because it is grounded below sea level and is potentially unstable in light of global warming and sea level rise (Weertman, 1974). As the onset areas of tributary fast flow seem to have been migrating inland at hundreds of metres a year (Bindschadler, 1997), understanding the flow in this region has become a priority in understanding the WAIS.

Interferometry has been able to identify regional flow patterns previously unknown (Joughin *et al*., 1999). A network of tributaries, coincident with subglacial valleys, has been identified which extend far into the ice sheet interior, providing the transition from slow inland flow to rapid ice stream flow. Tributaries that feed different ice streams flow from the same source area indicating that the flow of the ice streams is more interconnected than previously thought, and should be modelled collectively. Figure (1) illustrates some of the ice motion data discussed in the above study.

Ice flow through the Filchner Ice Shelf

The Filchner Ice Shelf (FIS) lies between Coats Land and Berkner Island in the southern embayment of the Weddell Sea. It is formed by the convergence of ice from the Slessor, Recovery and Support Force Glaciers, the Foundation ice stream, and ice flowing off Berkner Island and Coats Land. The ice shelf ocean interactions of the FIS are particularly important as FIS meltwater contributes to the formation of Antarctic Bottom Water, which is a significant component of global thermohaline circulation (Foldvik *et al*. 1985). Nicholls (1997) showed that climate warming would reduce FIS basal melt, thus increasing the longevity of the ice shelf, and would also reduce the production of Antarctic Bottom Water.

The InSAR derived ice velocities, see Figure (2), are being used to help provide accurate baseline flux rates and inputs for ice shelf models in order that we can begin to quantify the impacts of predicted changes. In studying the major contributors of ice to the FIS it has been revealed that the Foundation Ice Stream is a significant contributor where previously it was thought to contribute only to the Ronne Ice Shelf. Small contributions of ice from Berkner Island and Coats Land have also been identified. Using the principle of hydrostatic equilibrium and altimeter elevation data, it is possible to calculate the ice thickness for floating ice (Vaughan *et al*. 1995). Using thickness and velocity data, fluxes are calculated for gates across the tributary glaciers and the ice front. These flux estimates will be published elsewhere.

Accuracy of Ice Velocity Estimates

The errors in applying the speckle tracking method vary with region and with the presence of reliable reference values. In one region close to ice streams B and C in the WAIS there were sufficient reference data to both control bias errors and to check accuracy. For this area the standard deviation of the mean was ~ 3.5 m/a for 5 x 5 km cells with speed less than 90 m/a. This represents probably the best one can do with the speckle tracking method. For the FIS data there is an additional error contribution because of the unknown tidal height difference between the 2 data acquisitions. This will affect the range component of velocity and, together with the lack of velocity control in this area, will lead to much larger errors, around 30 m/a bias errors are possible dependent on direction. However, even with these errors the ice speeds in this region can be so large, ~ 1 km/a, that the results are still useful.

Azimuth Streaks and the link to ionospheric activity

Azimuth streaks in repeat-pass satellite interferometry have been observed with different processors, different ground stations and with different satellites. We have seen very similar patterns with the C-band satellites RADARSAT 1 and ERS 1 and 2. A related pattern has been observed with a much smaller L-band data set (5 JERS interferograms). The patterns seems to take 2 forms (at least at C-band): One in which many streaks occur often oblique to the beam direction and can exist over along-track distances of many hundreds of kilometres to over 1,000 km. Secondly, more or less isolated azimuth streaks have been observed, perhaps a few per 100 km scene. All the observations we are aware of have been at high latitudes close to, or in, the region referred to as the auroral oval. Figure 3 is an illustration of C-band ‘azimuth streaks’ from RADARSAT data in Antarctica which showed some streaking for ~ 1000 km along track. The peak-to-peak modulation in azimuth shift for this example is approximately 1 metre and most of the streaks are oblique to the beam direction but a few are close to the beam direction. In fact, by editing the signal data for a few range lines we are sure that even the streaks that are close to the range direction are slightly displaced in angle from the beam centre direction. Other tests have been carried out to try to identify other potential satellite or processing problems which might be associated with the streaks, to no avail.

Without an apparent technical or processing explanation, we propose that the observation of azimuth shift modulation in polar repeat-pass InSAR is a consequence of the pseudo Doppler that can be caused by varying ionospheric propagation conditions during the aperture time. At C-band a satellite SAR footprint is illuminated for approximately 0.5 seconds, during this time the satellite travels over 3.5 kilometres. The line-of-sight illumination of a footprint sweeps out an along-track arc of a few hundred meters to ~ 2 km at altitudes of 50 to 400 km above the Earth's surface. If the integrated electron density of the line-of-sight path changes significantly in the time the footprint is illuminated, then the phase history of the ~ 600 pulses that illuminate that footprint will be corrupted and it will not necessarily be mapped to the correct azimuth position during processing. Tropospheric propagation problems can also lead to well known interferogram phase errors (Tarayre and Massonet, 1996) but the focussing operation will preserve the correct azimuth mapping in this case because the propagation phase shift occurs at essentially the same range as the terrain. In summary, a tropospheric propagation problem can add a constant shift to the phase history of a particular, azimuth unfocussed SAR footprint, but varying ionospheric propagation conditions may add a varying phase shift which on processing may produce an azimuth positional mapping slightly different from that due to the range history alone.

We are testing this hypothesis in 2 ways: First by attempting a direct correlation of the presence of azimuth streaks with ionospheric activity. This can be studied and monitored in a number of ways including use of auroral radars, e.g. the SuperDARN network, and by use of magnetometer data. To date, we have concentrated on magnetometer data as the large currents associated with ionospheric activity lead to changes in surface magnetic field. In this work we have compared data from the MACCS magnetometer array maintained by Boston University, Augsberg College, and GSC Canada, with IQL data derived from ESA ERS tandem mode data over northern Canada. Many passes of tandem data over North American have been processed by Atlantis Scientific, Ottawa. Quality control notes (van der Kooij, 1999) reveal that a number of long passes have been affected by azimuth streaks in the coherence image. Two pairs of passes were selected which cover almost the same terrain in western Arctic. The ERS-1/2 pair of November 12 & 13, 1995, (19:16:35-19:24:50, ERS-1, 22632; ERS-2, 2959) show streaks in the coherence image. Magnetometers at Resolute (RE) and Gjoa Haven (GH) are within 250 km and 850 km of the swath, respectively. Both show significant and correlated variations at that time. By contrast, the ERS-1/2 pair of November 25 & 26, 1995, (19:07:31-19:16:37, ERS-1, 22818; ERS-2, 3145), is within 300 km of the previous pass and show no streaks in either the coherence or phase images. Magnetometers at Cambridge Bay (CB) and Resolute (RE) are within 250km of the swath and show very little activity. We have found no pairs showing streak activity without an indication of ionospheric activity through variations in the magnetometer array data.

Secondly, we use a simulator to test the influence of changing ionospheric conditions on azimuth shift: Simulated distributed target clutter (range focussed but azimuth unfocussed) is generated using a random array of independent scattering centres convolved with the antenna pattern weighting and the appropriate quadratic phase variation for satellite radar ranges. The clutter is generated both with and without an additional phase modulation due to a 'phase screen' at a particular height above the earth's surface. This additional phase change is designed to simulate the effect of a varying ionospheric electron density. The modified and unmodified clutter is then processed and the azimuth shift calculated. The simulator is straightforward and does not treat earth rotation or range cell migration. Each run is done at a particular radar range and complex multi-looking is possible.

The initial results from the simulator compared to the observed results are:

- A relatively small phase modulation in a phase screen at ionospheric altitudes can lead to the sort of azimuth shift observed in the Arctic and Antarctic. The associated phase shift in the interferogram is also relatively small and could explain why some azimuth shifts have been observed without an obvious associated phase problem.

– The along-track scale of the azimuth shift variability from real data is comparable to the real beamwidth, as expected from the proposed mechanism.
– The effect will be more serious for L-band because the real beamwidth is larger and because the ionosphere affects L-band much more than C. This has been confirmed with 5 JERS-1 pairs collected over Bylot Island in the Canadian Arctic.
– Azimuth shift in unfocussed data (see Joughin, 1996) will be more complicated because it can also involve topography (baseline dependent), terrain movement in range, and both tropospheric and ionospheric propagation effects.

Summary

Speckle tracking is an appropriate technique to increase the applicability of repeat-pass InSAR to regions of high ice motion, longer temporal separation and 'patchy' coherence. One of the limitations of speckle tracking, the so-called 'azimuth streak' problem, has been shown to be associated with fine scale ionospheric disturbances in polar auroral regions. Further study of interferometric azimuth shift is planned to hopefully understand better polar electron density variations, and as a way of identifying and possibly minimizing the effect of variations in ionospheric propagation on differential phase from repeat-pass interferometry.

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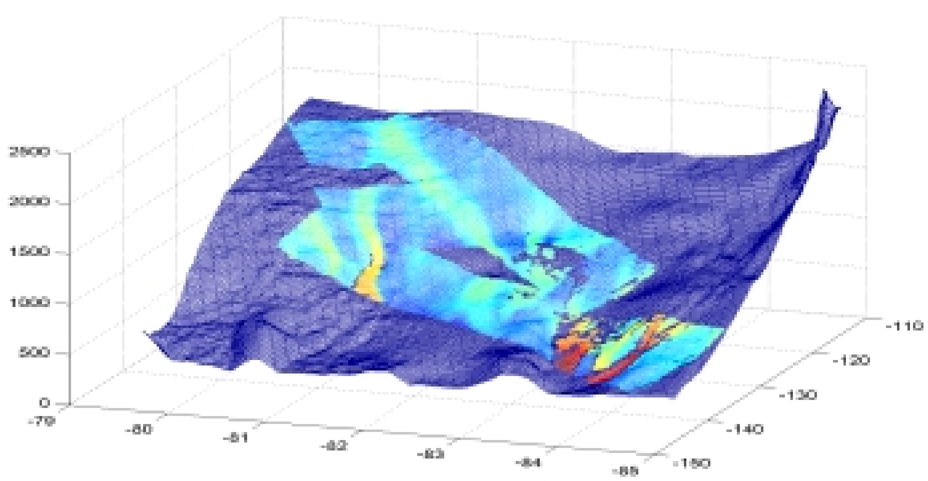

Figure 1.
Perspective view of part of the West Antarctic Ice Sheet showing some of the ice speeds derived from speckle tracking as a colour overlay on a mesh model of the topography. The highest speeds (> 400 m/a, red) occur in the lower right region and correspond to streaming flow in the 2 arms, B1 and B2, of ice stream B. Tributaries flowing into both the stagnant ice stream C and ice stream D can be seen to originate from the same region (top centre).

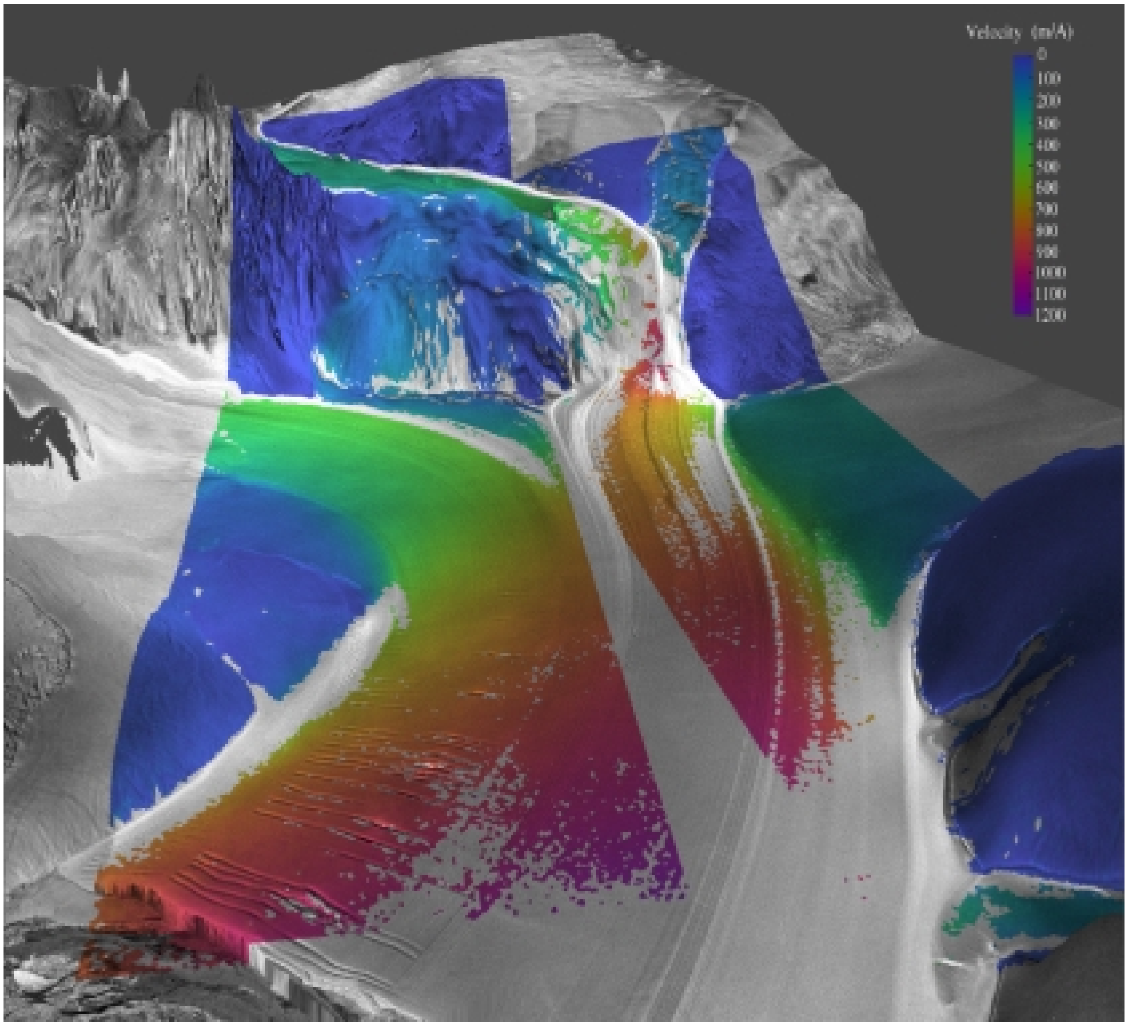

Figure 2.
Perspective view of the Filchner Ice Shelf looking south towards the west end of the Shackleton Range. Coats Land is on the left and Berkner Island on the right. The background image is from the SAR mosaic created by the Byrd Polar Research Center, Ohio State University from RADARSAT imagery collected in the RAMP. Speckle tracking has been used to estimate the ice velocities, shown as a colour overlay on the image. The highest velocities (purple) are around 1.2 km/a while blue indicates slow ice movement. The major sources of ice are the Slessor Glacier (left), the Recovery Glacier (above the Slessor), and on the right the combined flow from Support Force Glacier and the Foundation Ice Stream. An un-named glacier joins the Recovery Glacier close to the steep and fast region as it enters the floating Filchner Ice Shelf.

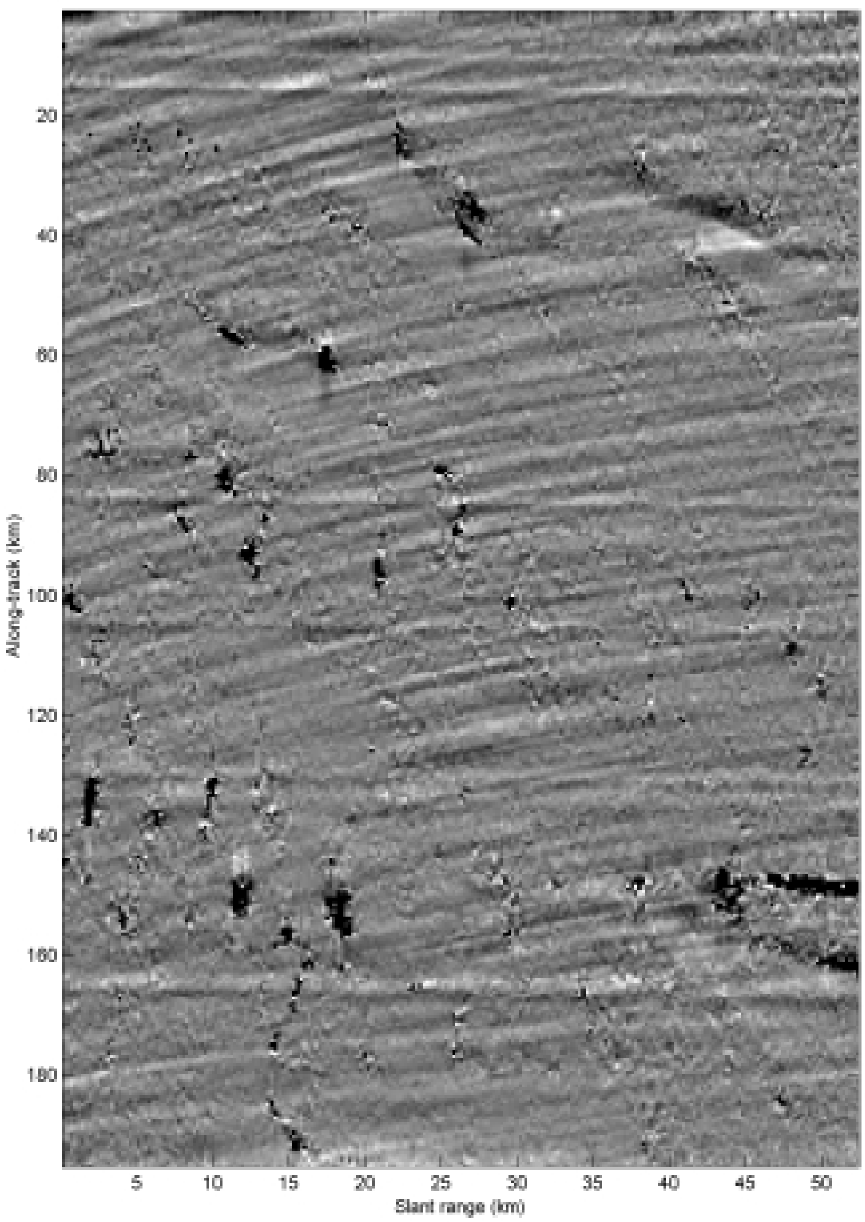

Figure (3)
Illustration of ‘azimuth streaks’ in an image of azimuth shift for an Antarctic InSAR pair. In this case the azimuth shift data has been high pass filtered to accentuate the streaking and to minimize the azimuth component of ice movement. The image is presented in slant range, the ground range swath is ~ 110 km. The peak-to-peak modulation in azimuth pixel shift is typically 1 m for this data.