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Demonstration of ERS Tandem Mission SAR Interferometry for Mapping Land Fast Ice Evolution

by T. Hirose, P.W. Vachon

RÉSUMÉ

Une série temporelle d'interférogrammes de la mission en tandem d'ERS à partir de paires d'images RSO du chenal de Resolute, Territoires du Nord-Ouest, Canada. Ces images contiennent de l'information sur l'évolution des glaciers terrestres au cours d'une saison et confirme l'évidence du mouvement relatif des glaces le long des fractures.

SUMMARY

A time series of interferograms from ERS tandem mission SAR image pairs over Resolute Channel, Northwest Territories, Canada, contain information on the evolution of land fast ice over the course of an ice season, and provide evidence of relative ice movement along fractures.

INTRODUCTION

Canada's Northwest Passage spans the Arctic Archipelago and serves as an important shipping corridor for transporting minerals and oil out of the north and as a resupply route for northern coastal communities. Shipping begins after ice break-up and continues until freeze-up.

Ice bridges form between the Arctic islands during freeze-up and remain consolidated until the spring thaw. It is well known that the consolidated ice weakens during the spring period due to increasing air temperatures. This period is followed by a break-up of the ice that is discharged into the open waters of Baffin Bay. It is hypothesized that the weakening of the ice will result in micro-movements (e.g. fractures and relative displacements due to tidal and wind forcing) which may be detected using interferometry. As such, repeat pass synthetic aperture radar (SAR) interferometry could be a useful tool for the early detection of ice break-up. A time series of ERS tandem mission (ERS-l followed by ERS-2 24 hours later) interferograms have been processed over Resolute Channel, Northwest Territories, Canada (see **Figure** I). The interferograms span October 1995 through May 1996 and terminate with the conclusion of the tandem mission. Coherence and differential phase products were generated for each image pair. The temporal evolution of the land fast ice is evident in the scene coherence. Relative displacements along ice fractures are evident in the differential phase.

BACKGROUND

Repeat pass interferometry is a well-proven technique for measuring small changes on the earth's surface. Details of the methodology and its requirements are discussed at length elsewhere (Gens and van Genderen, 1996, is an example of a recent interferometry review). Basically, two mutually coherent SAR images are required. This imposes the following key restrictions on the data:

1. The geometry of the two passes must be similar (i.e., the baseline must be small, with the perpendicular component $B_n < 500$ m in the case of the ERS SARs);
2. The azimuth antenna pointing for the two passes must be similar (i.e. the difference between the Doppler centroids $?f_{dc}$ must be small compared to the radar's pulse repetition frequency, which is roughly 1680 Hz for our data);
3. The scene must remain stable at the scale of the radar wavelength (5.6 cm) over the time span between passes (24 hours in the case of the ERS tandem mission).

If these conditions are met, then the phase difference between the two images could contain information on the scene topography, as well as differential displacement at the scale of the radar wavelength (5.6 cm in the case of the ERS SARs) and surface change over the time span between passes. Useful extraction of topography or differential displacement requires accurate knowledge of the interferometric baseline, and an absence of phase aberrations, which could be caused by propagation of the microwaves through the atmosphere. The coherence (magnitude of the complex correlation between the two images) is a measure of the degree of phase correlation between the images and is very sensitive to changes in the scene. The coherence is estimated over a kernel of finite spatial extent.

◆ T. Hirose is with Noetix Research Inc., 265 Car1ing Ave., Suite 403, Ottawa, Ont. K1S 2E1 Canada, Phone: 613 236-1555, Fax: 613 236-1870, E-mail: Tom.Hirose@noetix.on.ca

◆ P.W. Vachon is with the Canada Centre for Remote Sensing, 588 Booth Sto, Ottawa, ON K1A OY7 Canada, Phone: 613 995-1575, Fax: 613 947-1385, E-mail: paris.vachon@ccrs.nrcanogcoca

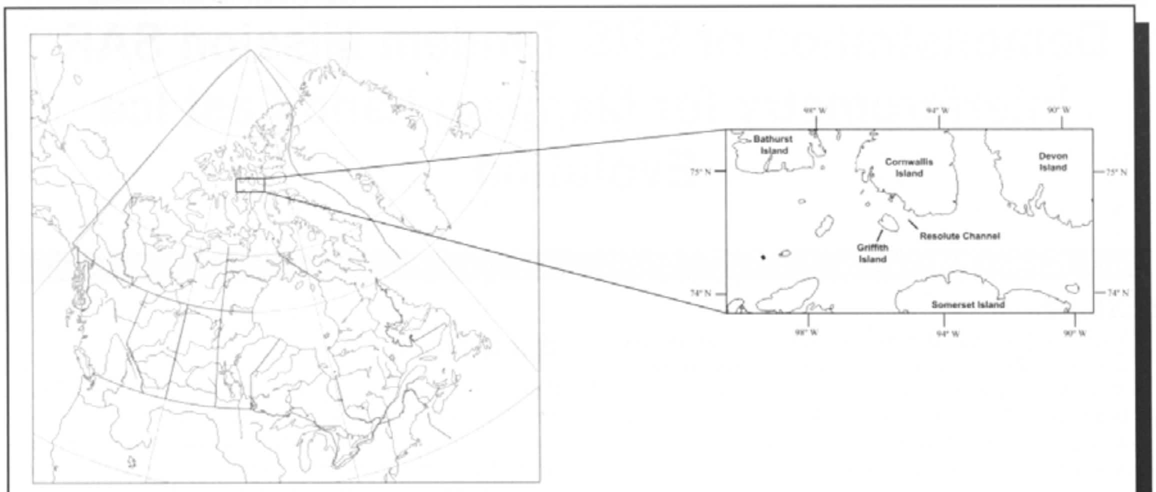

Figure 1.
Map of study site.

DATA SET

ERS tandem mission data were chosen for this study since they are readily available, are well proven in interferometry applications, and have only 24 hours between subsequent acquisitions. This is the minimum time difference from any polar orbiting SARs available to date. Furthermore, the 10-month long tandem mission produced many image pairs to choose from for this study. Resolute is the site of a RADARSAT SAR calibration transponder, which was undergoing routine observation by the ERS SARs during the tandem mission.

The marginal ice zone (MIZ) has been previously observed. using satellite repeat pass SAR interferometry (Dammert and Hagberg, 1994). Here, we considered a time series of observations over the course of the winter. We present three of those data sets, as summarized in **Table1**. These data are just a few of the total data set available, but were chosen as representative of the evolution in ice conditions over the course of the winter ice season. The data were processed to standard repeat pass interferometry products using methods that are described elsewhere (Vachon *et al.,* 1995) (Vachon *et al.,* 1996). The resulting SAR images, coherence maps, and flat-earth corrected phase images are shown in **Figure 2**. The flat-earth phase is essentially a measure of topography over the land regions, but is a measure of differential position shift at centimetre scales over the relatively flat ice regions.

Table 1.
Summary of Resolute Channel ERS tandem mode coverage considered. B_n is the perpendicular component of the interferometric baseline and Δf_{dc} is the difference in Doppler centroid between the ERS-2 and ERS-1 observations.

Dates	Time UTC	A/D	Absolute Orbits	Relative Orbit	B_n [m]	Δf_{dc} [Hz]
22/23 Oct '95	03:23	A	22322/2649	290	16	-254
22/23 Dec '95	18:20	D	23204/3531	170	19	-249
10/11 May '96	18:20	D	25208/5535	170	86	-234

DISCUSSION

By late October, based on the SAR image alone, ice is present throughout Resolute Channel and surrounding Griffith Island. However, the lack of coherence indicates that this is unconsolidated, moving pack ice, except in the embayments along the south coast of Cornwallis Island, where a weak coherence signature is found. This suggests that the ice in the embayments is land fast, but is evolving significantly (probably thickening) over time scales of 24 hours. The land is of reasonably uniform phase since the interferometer is insensitive to topographic phase when the baseline is small (see **Table 1**). However, there are regions of low coherence (high phase noise) on the land due to stochastic changes on the surface at the scale of the radar wavelength over the time span between the two passes (i.e. a loss in scene coherence which could be caused by snow accumulation or daytime melting).

By late December, the ice has solidified and has bridged Resolute Channel. Dark lines are visible in the coherence map along the shoreline and across the land fast ice. The lines arise from phase discontinuities that are visible in the phase image. The land fast ice is subject to the effects of tidal and wind forcing, which can cause differential movement along fracture zones and at ice/land boundaries. The phase discontinuity causes a loss in estimated coherence since spatial averaging is required for the coherence estimator. The phase gradient and phase discontinuities across the ice are differential effects, likely caused by differences in tide levels and wind forcing between

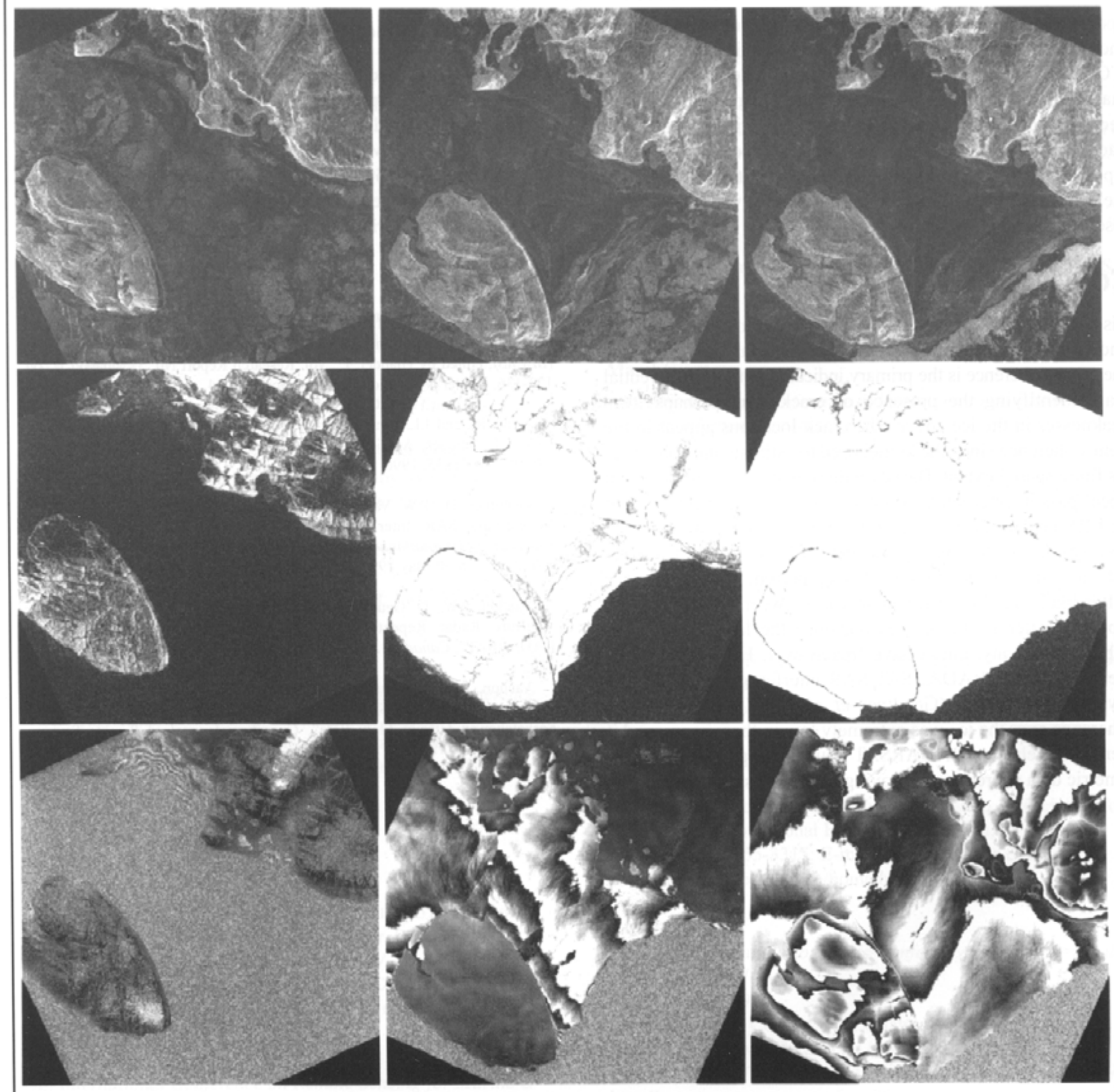

Figure 2.
Tandem mode images of Resolute Channel for 22/23 Oct. '95 (left), 22/23 Dec. '95 (centre), and 10/11 May '96 (right). The upper row is the image from the first date of each pair. The second row is the 24 hour interval scene coherence (0 is black while 1 is white). The third row is the interferometric phase following flat-earth phase correction (each cycle from white to black represents 2π radians). In each case, north is up and east is to the right. Each image covers roughly 37-km by 37-km.

the two acquisitions. Note that the land is again of rather uniform phase since the interferometric baseline is small.

By May, the extent of land fast ice has progressed down Resolute Channel and Griffith Island is nearly surrounded by land fast ice. There are not any cracks associated with phase discontinuities and resultant dark lines in the coherence map of the land fast ice. However, some residual lines are evidence of old cracks, probably due to enhanced local roughness compared to the surrounding ice surface. Presumably the land fast ice has grown in extent and strength since the December case. There is still a phase gradient across the land fast ice, again believed to be due to differences in tidal forcing. From the image (top-right), it is evident that an ice lead has opened up between the land fast ice and the nonconsolidated pack ice that is further offshore. The ice lead appears bright due to wind roughening of the open water. Note that the land shows more topography-induced phase structure than the other two cases, since the interferometric baseline is larger for this case (**Table 1**).

Certain patterns are visible in the amplitude and coherence images of the land fast ice in Resolute Channel in both the December and May images. Presumably, prior to break-up, cracks similar to those seen in the December image would appear. Unfortunately, our time series terminated in May 1996 due to the end of the ERS tandem mission, so we are unable to observe this event.

CONCLUSIONS

It is apparent that one-day interval interferograms from the ERS tandem mission permit observation of land fast ice evolution. The scene coherence is the primary indicator, with the differential phase identifying the presence of cracks and perhaps local weaknesses in the ice cover. The crack locations appear in the scene coherence since the kernel used to estimate the coherence has finite spatial extent. Based on these results, we propose that repeat pass interferometry observations with characteristics of the ERS tandem mission could be used to predict the onset of ice break-up. Unfortunately, we do not have any data for this test site that extends into the break-up period.

It is likely that longer time intervals between passes could be supported later in the ice season, once the land fast ice has stabilized and any cracks have frozen over. Land fast ice has been observed in RADARSAT SAR interferograms having 24 days between passes (Geudtner *et al.,* 1997). However, the coherence over the ice was extremely low in these cases, and it seems unlifely that RADARSAT could be a practical interferometric data source for improving predictions ofice break-up.

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