Influence of Ionospheric Electron Density Fluctuations on Satellite Radar Interferometry

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Abstract. Evidence is presented that auroral zone ionospheric disturbances can influence satellite radar interferometry (SRI) obtained with the RADARSAT, ERS and JERS-1 satellites. Fluctuations in ionospheric electron density can lead to an azimuth shift modulation in synthetic aperture radar (SAR) imagery, which can be detected using SRI. Measurements of azimuth shift in SRI can help to differentiate ionospheric from tropospheric propagation problems, and to understand better the impact of the ionosphere on spaceborne SAR. Further, SRI azimuth shift modulation may be useful in mapping patterns of polar auroral zone ionospheric disturbances over large distances.

Introduction

Amongst the most important civilian applications for radar satellites are those associated with monitoring polar and sub-polar regions. In particular, SAR imagery provide essential information for operational ice reconnaissance, and is being used increasingly in support of polar terrain mapping and climate change research. However, more extensive exploitation of SAR and SRI for polar monitoring, especially using L-band (1.2 GHz) or lower frequencies, should consider the effect of polar ionospheric disturbances reported in this work.

In a recent example of the use of satellite SAR in support of Antarctic science, NASA and the Canadian Space Agency, CSA, co-operated in using the C-band Canadian satellite RADARSAT (operating at 5.3 GHz in a 800 km, sun-synchronous, dawn-dusk orbit) to produce the first high resolution radar image map of Antarctica. The 30 day Antarctic Mapping Mission also encompassed a more limited 6 day SRI data set which is being used to study glacial ice motion [Gray et al., 1998; Joughin et al., 1999].

Occasionally, the image correlation component in this work showed a modulation in optimum azimuth (along-track) registration. In fact, very similar observations, dubbed 'azimuth streaks', had been made previously with ERS (C-band) data [Joughin et al., 1996]. We present evidence that the effect is geophysical and related to small scale polar ionospheric disturbances.
It is well known that variations in tropospheric propagation conditions affect satellite SRI [Goldstein, 1995; Tarayre and Massonet, 1996]. Evidence will be presented to show that along-track changes in ionospheric propagation can affect not only the phase but also azimuth focussing of SRI data such that a mis-mapping of the pixel in azimuth can take place.

'Azimuth streaking' and the ionosphere

Azimuth streaking is most clearly visible as a kilometer scale modulation in the position of optimum azimuth registration [Joughin et al., 1996]. When the modulation is large, the effect can also be observed in the coherence and phase. The patterns seem to take different forms. Firstly, many streaks can occur over along-track distances of many hundreds to over 1000 kilometers, often slightly oblique to the beam direction with a degree of obliqueness varying slowly along track. Secondly, more or less isolated azimuth streaks have been observed, perhaps a few per 100 km. Streaking has been observed from different satellites and with different processors, but apparently only from data collected relatively close to the auroral zones centred roughly on the north and south geomagnetic poles.

Figure 1 illustrates C-band 'azimuth streaks' from part of a RADARSAT Antarctic SRI pair. The gray tone in this image represents the shift in azimuth position for optimum registration of 1 km x 1 km windows from each pass. The peak-to-peak modulation in azimuth shift in this example is ~0.1 to 0.2of a pixel spacing (~5 m).
Most of the streaks are oblique to the beam direction but a few are close to the beam direction. Figure 2 is an average of the along-track azimuth shift across an isolated streak from another RADARSAT Antarctic SRI pair. The modulation is ~0.2 pixels or ~1 m in amplitude.

As our attempts to provide a technical explanation for the observed azimuth shift modulation failed, we investigated the possibility of a phase modulation caused by varying ionospheric propagation conditions during the aperture time. Variations in electron density in the ionosphere lead to changes in the refractive index [Bomford, 1980]. Trans-ionospheric radio wave propagation shows significant phase 'scintillation' at spatial scales down to less than 1 km, particularly in the auroral zones [Yeh and Liu, 1982]. This implies that a satellite side-looking radar could experience phase changes when traversing the auroral zone. At C-band, a satellite SAR footprint is illuminated for ~0.5 sec; during this time the satellite travels ~3.5 km. 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.

The path length change, d s, associated with propagation through an ionosphere with a path integrated electron density, N_t, is ds = -a N_t /f ^{2}, where the constant a =40.3 if the frequency f is in Hz and N_t is a number of electrons per m^2 [Bomford, 1980]. The associated phase shift for 2-way propagation is -2kds, where k is the propagation wavenumber. It follows that a change in N_t of ~3.10^{15} m^{-2} would produce a phase change of ~1 radian at C-band and over 4 radians at L-band. As a background N_t of ~10^{17} m^{-2} is not unusual, this shows that a relatively small change in N_t can led to a significant phase shift. Satellite measurements [MacDougall, 1990] confirm that scintillation onset can be accompanied by an increase in both N_t and fluctuations in N_t. Electron flux in the auroral zones is strongly influenced by the near-vertical magnetic field lines. If the SAR image plane moves past a kilometer scale tube-like or cylindrical change in electron fluxcentred on amagneticfield line, or the imaging plane coincides approximately with predominantly magnetic east-west sheet- or arc-like electron fluxes, then the change in N_t could occur in the spatial scale necessary to cause SRI azimuth shift.

Correlation between azimuth streaks and ionospheric activity

Magnetometer data from the MACCS (Magnetometer Array for Cusp and Cleft Studies) array and the GSC (Geological Survey of Canada), have been compared with SRI data derived from ERS tandem mode data over northern Canada. Many passes of the ERS data have been processed by Atlantis Scientific, Ottawa, including two pairs of passes which cover almost the same terrain in the western Arctic. The ERS-1/2 pair of November 12 and 13, 1995, (19:16:35-19:24:50, ERS-1, 22632; ERS-2, 2959) show streaks in the phase and coherence. At that time, magnetometers at Resolute and Gjoa Haven, within 250 km and 850 km of the swath, respectively, show significant variations in magnetic field, indicative of ionospheric activity. By contrast, the ERS-1/2 pair of November 25 and 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 and Resolute are within 250 km of the swath and show minimal variation. Streaks have not been observed without some indication of ionospheric activity. Magnetometer data, available at http://space.augsburg.edu/space/index.html, may help SRI data users avoid passes adversely affected by ionospheric activity.

Use of a simulator to test the influence of a ‘phase screen’ on azimuth shift.
Azimuth unfocussed SAR clutter can be simulated by convolution of random number arrays with the antenna pattern weighting and the quadratic phase variation appropriate to the radar range variation. This concept has been extended by creating a geometric model whereby the radar beam views the Earth through a ‘phrase modulation screen’ at a particular height above the Earth’s surface. This is designed to simulate, in as straightforward a manner as possible, the effect of varying electron density at an intermediate range to the scene being imaged. The simulator compares results with and

without the phase screen, and shows that a relatively small effect at an intermediate range can lead to azimuth shifts and phase changes similar to those observed with the C-band radars.

Figure 3 shows an example of C-band simulator results. A 0.4 radian step increase in phase over 200 pixels (~1 km) is used as the ‘phase screen’ (upper plot) to simulate a band of increased electron density. The resulting differential phase for azimuth focussed and unfocussed data is shown in the middle plot for the phase screen applied at ground level and at 0.4 times the satellite height. When applied at ground level the phase screen is recovered in the processed differential phase, and there is no azimuth shift (lower plot). With the screen applied in the clutter simulation at 0.4 times the satellite altitude, the peak-to-peak azimuth shift is ~0.3 pixels. This shows that relatively small phase modulation in a phase screen at ionospheric altitudes can lead to the type of azimuth shift observed in the Arctic and Antarctic (see Figure 2).

Effect of frequency

The ionosphere will influence an L-band (JERS-1 is 1.275 Ghz, ? =24cm) SAR more than an equivalent C-band SAR for two reasons: First, the phase shift arising from a particular integrated electron density will be larger because of the basic dispersive nature of the phenomena, and secondly, the beamwidth is broader and therefore the possibility of significant spatial change in electron density in the aperture time is larger.
Five L-band SRI pairs have been created from Japanese JERS-1 data over Bylot Island in the Canadian Arctic. Figure 4 illustrates the azimuth shift from these data, and confirms that it is significantly larger than the typical C-band values. Also, the scale of the along-track azimuth shift variability is longer, as shown by an L-band version of the simulator. While we cannot compare C- and L-data collected at the same time and place (or with the same beamwidth), even this limited L-band data set strongly supports the concept that ionospheric electron density fluctuations are causing the azimuth shift fluctuations.

Summary

The link between auroral zone ionospheric disturbances and C-band SRI azimuth streaks is supported by three observations. First, the presence of streaks has been correlated with ionospheric activity through use of magnetometer records. Second, simulations show that the magnitude and along-track scale of the observed SRI azimuth shifts can result from credible integrated electron density variations. Finally, a larger effect has been observed, as expected, with the L-band JERS-1 SRI data set. In summary, azimuth shift modulations on a km scale (C-band), or 5-10 km scale (L-band), are an indicator of ionospheric propagation problems. Further work will examine whether a first order SRI phase correction may be possible from the azimuth shift.
Finally, can the existing and future SRI polar data sets contribute to the study of auroral zone ionospheric disturbances? There are 3 disadvantages to the use of SRI. There may be a loss of coherence due to the time between passes, the results represent

the composite effect from both passes, and the SAR imaging geometry will impose a directional sensitivity to the SRI mapping of ionospheric disturbances. However, the potential benefit of an essentially synoptic view of a 2-dimensional ‘shadow’ of the along-track gradient of small scale disturbances over large distances may be useful in the study of the complex 3-dimensional structure of auroral ionospheric disturbances, especially when combined with simulations and other data. It remains to be seen whether this can be realised.

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Figure 1. Illustration of azimuth shift from an Antarctic SRI pair (81.3S, 122.1W) acquired by RADARSAT on 26 Sept. and 20 Oct. 1997. The data has been filtered to accentuate the streaking and to minimize the azimuth component of ice movement. A dense pattern of slightly curved streaks somwhat oblique to the range direction is visible, together with a few linear streaks approximately in the range direction. The peak-to-peak modulation in azimuth shift is typically 50 cm for this data. The small black patches are data gaps.

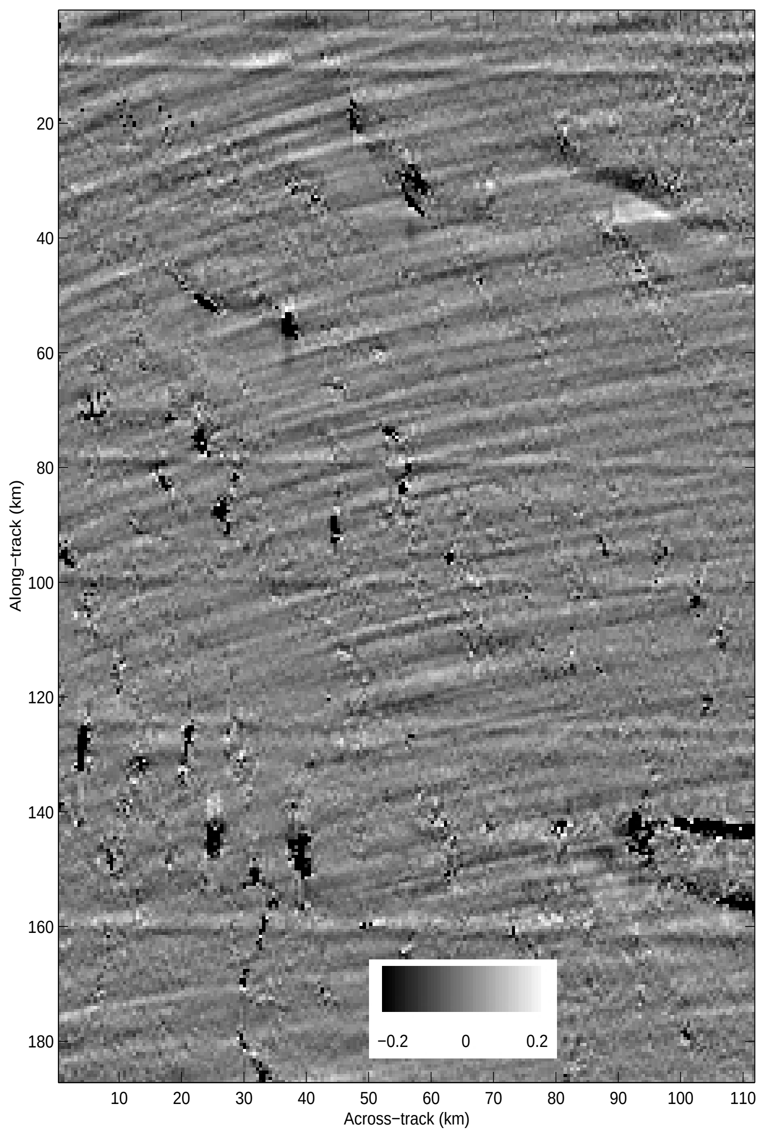

Figure 2. Average azimuth shift across an isolated, linear, azimuth streak. The azimuth pixel spacing in this RADARSAT example (80.7S, 39.1W on 23 Sept. and 17 Oct., 1997) is ~ 5 m.

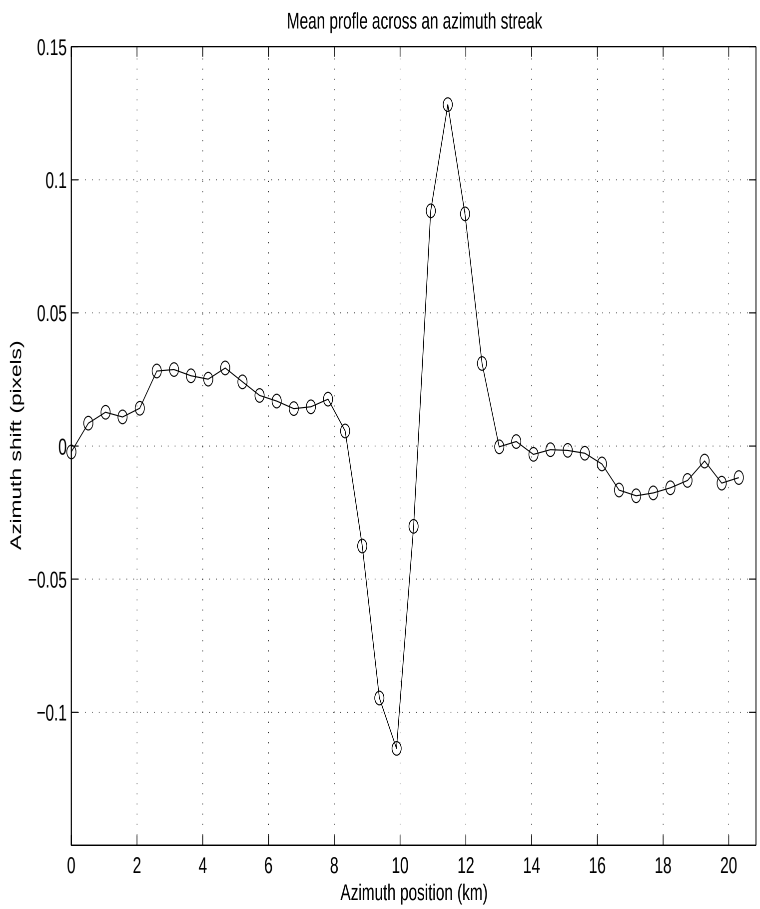

Figure 3. Simulated results for a 0.4 radian 'phase screen' (upper plot) applied at ground level and at 0.4 times the satellite altitude (H = 800 km). The middle plot shows the effect of the phase screen on the focussed and unfocussed SRI phase, and the lower plot shows the azimuth shift in pixels from the focussed data.

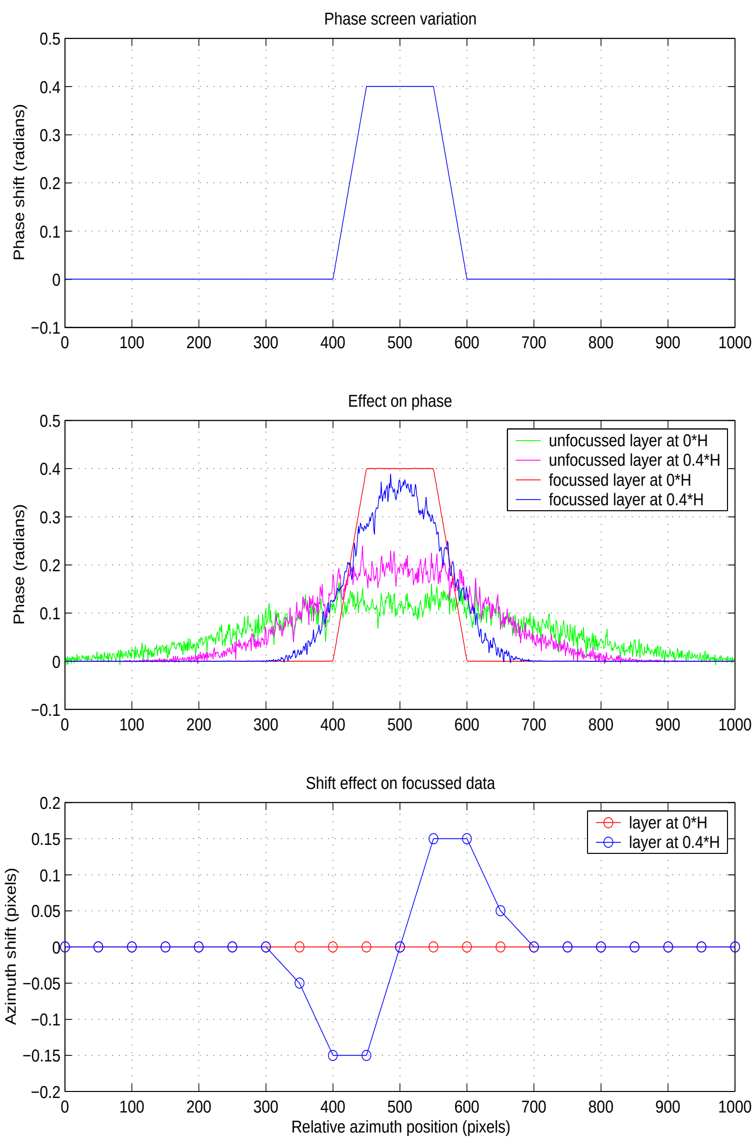

Figure 4. L-band azimuth shifts from 5 JERS-1 SRI pairs. Each scene is ∼ 75 x 75 km and the greater magnitude and larger along-track (vertical) scale of the azimuth shift modulation in comparison to the C-band results is apparent. The black areas are data gaps due to low coherence, particularly in the sea-ice or open water between Bylot Island (lower right) and Baffin Island (lower left).