Ocean Surface Feature Detection With the CCRS Along-Track InSAR

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SUMMARY

From 1993 to 1996, the Canada Centre for Remote Sensing (CCRS) owned and operated a C-band ($\lambda = 5.656$ *cm) airborne synthetic aperture radar (SAR) with along-track interferometric capabilities. This along-track InSAR used a microstrip antenna mounted on the right side of the aircraft, which could be electronically divided into two sub-antennas with phase centres separated by 0.46 meters along the flight direction. In June, 1994 the CCRS InSAR was flown in a series of missions over the Bay of Fundy in conjunction with a dune survey experiment undertaken by the Canadian Hydrographic Services vessel, "NSC Frederick G. Creed". The ability of the InSAR to measure surface current velocities and to use them to enhance the detection of subsurface features was investigated, and compared with results available from the ship based sonar survey and from ERS-1 satellite SAR imagery. Experiments in 1995 continued this work and also examined the ability of the InSAR to detect moving ship and wake signatures. The results indicate that the CCRS airborne along-track InSAR is capable, under the right conditions, of detecting changes in ocean bottom topography, of providing a high resolution snapshot of the surface currents in a large area, and of enhancing the detection of moving targets on the ocean surface.*

INTRODUCTION

Conventional SAR imagery has been used to study the ocean for many years. Short wavelength (centimeter scale) capillary and gravity waves on the surface of the water are affected by geophysical parameters, such as the wind stress, the local currents, and larger scale gravity waves. Bragg scattering occurs between the microwaves transmitted from a SAR and any surface which has modulations of the appropriate wavelength, $\Lambda = n l \,/\, (2\sin\Theta)$, where Θ is the radar incidence angle, l is the radar wavelength (5.656 cm in the case of the CCRS InSAR) and n is a positive integer. In the case of water, which has a large dielectric constant, this is the main scattering mechanism and any mechanism which affects the Bragg-scale waves will also affect the scattering properties of the ocean at radar wavelengths. The precise relationship between the radar cross section (RCS) of the ocean and the relevant geophysical parameters is difficult to define, however, and different models have been suggested [e.g. Alpers et al., 1981; Hasselmann et al., 1985; Moore, 1985].

Along-track InSAR provides a more direct way of observing certain properties of the ocean than conventional SAR imagery. The phase difference between the radar images received by two antennas separated along the flight path of the aircraft is used to directly measure the velocity of each target pixel in the radial direction (approximately parallel to the radar boresight). This type of measurement is independent of the target's RCS, removing one layer of complexity from the problem. It is still necessary to relate the radial velocity to the desired geophysical parameters, but this is, in principle, a simpler procedure. Recently, several groups have used the along-track interferometry technique to study ocean waves [Marom et al., 1991; Schuchman et al., 1992; Goldstein et al., 1994], currents [Goldstein et al., 1987, Shemer et al., 1993; Ainsworth et al., 1994] and ship wakes [Orwig et al., 1992; Thompson et al., 1993].

Between May 31 and June 3, 1994, the CCRS along-track InSAR carried out a series of flights near the Minas Basin in the Bay of Fundy. The tides in this area are among the most dynamic in the world and produce strong currents with significant spatial and temporal variability. There are also several interesting underwater features in this area, such as the Scots Bay and Margaretsville dune fields. Conventional SAR imagery has previously been used to detect dune fields using the modulations in Bragg scattering caused by the changing depth affecting the current velocity over the dunes [van der Kooij et al., 1995]. This is useful, because it is important to monitor bottom topography and especially the location of potential shipping hazards such as shoals or dune fields. Currently this information is usually gathered through ship based surveys. In the Bay of Fundy mission, the goal was to determine whether along-track InSAR could be used to enhance the detection and mapping of these types of subsurface features and also to investigate the ability of the InSAR to produce detailed maps of the currents in this dynamic environment. The Canadian Hydrographic Services vessel, NSC *Frederick G. Creed*, was engaged in a dune survey in the Minas Channel during this time period. This allowed the sonar data from the survey to be used to validate the conclusions drawn from the InSAR data.

From June 22 to June 27, 1995, the CCRS airborne SAR participated in the MARCOT ‘95 trials off the East coast of Nova Scotia. During that time period the InSAR was used to acquire ship and wake signatures, as well as to map the currents during a flood tide at the entrance to Passamaquoddy Bay. This data set will also be reviewed.

In the next section of this paper, the equipment used in both the airborne InSAR and the ship based sonar will be described. Then the results obtained by the airborne InSAR in terms of surface current mapping are described. Next, the ship and wake signature data are considered. Finally, the ability of the InSAR to detect subsurface features is examined and the results are compared with those from the ship based sonar survey and from ERS-1 SAR data. Some conclusions about the utility of the system are presented.

EXPERIMENTAL SETUP

CCRS InSAR

The structure and operation of the CCRS C-band SAR has been described in detail previously [Livingstone et al., 1987; Livingstone et al., 1995]. In 1991, this system was modified to include an across-track interferometric capability by adding a microstrip antenna on the right side of the aircraft [Gray et al., 1992]. In 1993, the InSAR system was further enhanced to allow along-track interferometry by dividing the microstrip antenna into two separate sub-antennas with phase centres separated by d = 0.46 meters along the aircraft. The main C-band antenna, located underneath the aircraft, transmits horizontally polarized pulses which are received and recorded separately from each of the microstrip antennas. The microstrip antennas have asymmetric azimuth weighting functions which results in each antenna having a main lobe squint of approximately 1.1^0 in opposite directions. To compensate for this, the antennas are mounted with a dihedral having an included angle of approximately 2^0. This results in two-way transmit-receive sidelobes of better than -40 dB. In order to avoid azimuth ambiguities, the along-track InSAR is run at double the standard SAR pulse repetition frequency (PRF) with PRF/V = 5.1345 m^{-1}, where V is the aircraft velocity.

Both the transmit and receive antennas are steered in azimuth using data from a Litton inertial navigation system (INS) sensor head located directly above the main antenna, combined with a real-time clutter lock which ensures that the antenna boresights are steered to zero doppler. Each of the 2 receivers, connected to the 2 halves of the InSAR receive antenna, includes a matched real-time surface wave acoustic pulse compression filter. The range compressed data is recorded as 6 bit I and Q data and motion compensated post-flight using both the Litton INS and differentially processed GPS data. By using GPS phase, the aircraft position can be determined to sub-meter accuracy. A single motion compensation reference track is defined (constant altitude above the WGS-84 ellipsoid and constant track angle) and the phase of the received signal is changed to correspond to the 2-way range between the pixel centre and the reference track. To accomplish this, models are created to describe the positions of the 3 antenna phase centres in the aircraft body reference coordinate system. These positions are then transformed into the motion compensation reference frame using aircraft attitude information from the laser ring gyros in the INS. Phase calibration is always necessary to achieve accurate estimates of radial velocity. Any variation in the electrical path lengths associated with the two sub-antennas, or the two C-band receivers in the radar system, will change the differential phase and corrupt the radial velocity estimation. More importantly, however, any error in the measurement of the positions of the antenna phase centres will lead to a phase calibration problem. Although the antenna positions are well known with respect to the aircraft and the absolute position of the imaging plane (the zero Doppler plane) can be derived from the GPS data, the absolute attitude of the aircraft is subject to uncertainty because of drift in the laser ring gyros used in the INS unit. In particular, errors in the aircraft heading will lead to differential phase errors which in turn lead to radial motion errors. The best way to guarantee a reliable phase calibration is to find a large flat object with zero radial motion close to the object being imaged. Fortunately, coastal land serves this purpose if it is included in the image.

After the radar image from each along-track antenna has been processed to a single look complex SAR image, an interferogram is produced by multiplying one image by the complex conjugate of the other. The magnitude of each pixel in this interferogram is a measure of the corresponding target resolution cell's radar backscatter and its phase, Φ, is a measure of the target cell's mean radial velocity. This is because the doppler processed image from the second antenna represents the same scene as shown in the image from the first antenna but at a time which is later by the period taken for the aircraft (and thus the phase centre of the antenna) to travel the distance between the two antennas, $t = d / V$. In that time, a target with radial velocity, v, will have moved a distance vt parallel to the zero Doppler direction and thus its phase will have changed by $4p\, v\, t / l$, where l is the wavelength of the radar. The phase of the interferogram can thus be directly translated to radial velocity using $v = V l \; \Phi / 2 d p$, where the reduction by a factor of two is due to the fact that the same transmit antenna is being used for both InSAR antennas and so the effective difference between the transmit/receive zero doppler positions is only $d / 2$. The necessity of exactly registering both images prior to combining them in an interferogram adds some complexity, but is not a problem provided the physical separation and electronic path lengths associated with each antenna are known. If the target becomes highly decorrelated over the time interval, t, however, the two images will not be phase coherent and the interferogram will be meaningless. This is not a problem for the CCRS along-track InSAR, since $t = d / V$ is typically around 5 ms whereas the ocean decorrelation time at C-band is thought to be between 50 and 100 ms [Vachon et. al., 1994].

The first test of the CCRS along-track InSAR took place on January 12, 1994 and demonstrated that the radial velocity of a point target undergoing linear motion could be measured by the InSAR system to an accuracy of 0.1 m/s over the range from -7.5 m/s to +7.5 m/s, even though the test conditions on that day were highly unfavourable [Gray et al., 1994]. Distributed targets involve more complex imaging mechanisms than point targets, however, since it is the ensemble average of the velocities of many individual scatterers which is being measured, and factors such as velocity bunching [Hasselmann et. al., 1985] and decorrelation induced velocity smearing [Carande, 1994] are important. A 0.1 m/s velocity accuracy is thus the ideal limit for distributed targets, and 0.2 - 0.5 m/s is the typical range of rms uncertainties in the observed velocity measured over ocean targets.

CHS Survey Ship

The Canadian Hydrographic Service (CHS) of the Department of Fisheries and Oceans provided the survey ship NSC *Frederick G. Creed* to take part in this experiment. It was equipped with a SIMRAD EM1000 multibeam sonar, which had 60 separate beams, each of 3.3^0 by 3.3^0. These beams were spaced 2.5^0 apart in an angular sector covering $+75^0$ to -75^0 from the vertical so that as the ship moved they could be used in a pushbroom imaging mode. The insonification frequency was 95 kHz using a 0.2 ms CW pulse.

In standard survey mode, the ship cruised at 12-16 knots, mapping a swath of a few hundred meters on the ocean bottom. The size of the swath changed because the bottom footprint of each sonar beam varied from 2 m to 5 m at the depths where the surveys were being conducted. A typical survey of the Scots Bay dune field required approximately twelve hours. Since this corresponds to a full tidal cycle in which the water level could change by as much as 10 m, it was necessary to reference the bottom topography to depths below the WGS-84 ellipsoid rather than below the water surface. This was accomplished using differentially processed GPS data from a receiver on board the ship, which also allowed the x-y coordinates of the bottom topographical features to be converted to an accurate UTM map.

One other advantage of the differential GPS data was that it allowed estimates of the current to be made. This was accomplished by comparing the actual velocity of the NSC *Frederick G. Creed*, as obtained from GPS data, to its expected velocity derived from the ship heading and the screw revolution rate. The difference between these two velocity vectors was assumed to be the surface current velocity vector.

SURFACE CURRENT MAPPING

The InSAR measures the ensemble average of the velocities of all the scatterers in a given resolution cell. For ocean surfaces, these scatterers are assumed to be Bragg waves on the surface of the water, and their velocities are assumed to be the sum of their phase velocity, the local orbital velocity of the ocean waves in the resolution cell, and the mean local surface current velocity. The measured velocity is the ensemble average of the sum of the radial components of these three velocity contributions for each scatterer. There may also be a wind drift component which will simply add a constant velocity offset to all of the scatterers over a wide area. If a large number of resolution cells are averaged together, however, then the effects of any orbital motion are greatly reduced because the radial components of the orbital motion separated by one half wavelength in the direction of the wave’s travel will cancel. The phase velocity can also be neglected because it is usually so small that it is part of the noise in an InSAR velocity measurement. The phase velocity, c_p, of a Bragg wave with wavenumber $k = 2p / \Lambda$ is given by:

$$c_p = \sqrt{\left(\frac{g}{k} + \frac{s\,k}{r*}\right)\tanh\left(kH\right)} \quad \approx \quad \sqrt{\left(\frac{g\,l}{4p\,\sin\Theta} + \frac{4p\,s\,\sin\Theta}{l\,r*}\right)} \qquad (1)$$

Here, s is the surface tension coefficient, l is the radar wavelength, Θ is the incidence angle and $r*$ the average density of the column of water of depth H. For a typical incidence angle of 45^0, and using the CCRS InSAR wavelength of 5.656 cm, this corresponds to a phase velocity of 0.27 m/s, which is comparable to the noise in a velocity measurement of a typical ocean clutter cell. Thus, the main radial velocity component from an averaged block of resolution cells is typically due to the local surface current.

The Bay of Fundy exhibits extremely powerful tides and correspondingly powerful currents. During 1994 and 1995, two missions were flown over different areas in the Bay of Fundy with the intention of determining whether or not the CCRS InSAR could be used to produce detailed surface current maps around features of interest. Maps of both these areas are shown in Figure 1. In order to obtain a full vector plot of the currents, it is necessary to combine the radial velocity information from two different flight lines flown close together in time over the same area, but with nearly perpendicular aircraft track angles. The necessity of reorienting the aircraft on a new track and initializing the InSAR for data from a new flight line, means that the minimum time between tracks is approximately twenty minutes. Only currents which remain constant over this time period can be properly measured by this method. An example of the results obtained with this technique near Cape Split during a flood tide is shown in Figure 2. This image represents a 10.5 km by 10.5 km region, with each pixel’s colour mapped to velocity using a colour map from black (0 m/s) through red, orange, yellow and finally white (5 m/s). The arrows show the magnitude and direction of the current vectors for averaged regions of 250 m by 250 m centred at the base of each arrow. The shear current around the tip of Cape Split as the tide flows into the Minas Basin is clearly seen in the figure, as is the division of water flow between that which passes Cape Split and that which hits Cape Split directly and is then turned back into Scots Bay (SE of the area shown in the figure). The phase calibration of this image appears to be quite accurate, since all of Cape Split and the small portion of the

Nova Scotia shore visible in the NE of the image appear dark. This image represents a ‘snapshot’ of the currents over a wide area during a twenty minute period in the tidal cycle, and is in qualitative agreement with the current models available for this area. The image in the figure has been mapped to a UTM grid with North at the top of the image and East at the right. All other figures in this paper will follow the same convention unless specifically noted otherwise.

Figure 3 shows a 1600 m by 1600 m area NW of Cape split using the same colour map as Figure 2. In this image the velocity vectors were generated from 40 m by 40 m averaged regions. A distinct funnel effect can be seen as much of the current is directed towards a channel of faster flowing water (yellow and orange pixels surrounded by red) moving NE. Previously it had not been possible to measure the fine structure of the velocity vectors near Cape Split because the rapid shear currents and submerged rocks made it difficult for boats to approach. Sonar surveys of the areas near Cape Split reveal a deep trench running from SW to NE. Only the ends of this trench can be observed directly, however, due to the dangerous waters near the cape. The InSAR surface current map provides evidence that the trench extends all the way past Cape Split until it intersects the underwater extension of Cape Split, thus producing the observed funneling effect.

The Letete Passage at the entrance to Passamaquoddy Bay (See Figure 1(b)) is another interesting area in the Bay of Fundy, principally because of the complex current tidal patterns between the numerous small islands in this area. Figure 4 shows an InSAR magnitude image (equivalent to a standard SAR intensity image) of a 5 km by 5 km region around Letete Passage (the largest channel in the upper part of the image) with the InSAR derived surface current vector map superimposed as blue arrows. This image was obtained under much more difficult conditions than those imposed during the imaging of the Cape Split area. Here the bright islands in the image saturated the radar and made it difficult to observe the water. The current magnitudes were lower than in the Cape Split image (ranging from 0 m/s to 1.6 m/s) and thus the velocity values were closer to the noise floor of the radar. The day of the experiment was calm, which meant that there were fewer wind induced Bragg scale waves and the water was a dark radar target. In many areas (the ones where no velocity vectors are shown) this meant that the backscattered signal from the water was not strong enough to give meaningful velocity information. The relatively narrow channels between the islands also complicated the situation due to land shadow blocking some parts of the water. Despite this, the vectors shown in the figure are consistent with a flood tide as water passes from the Bay of Fundy through Letete Passage and Little Letete Passage into Passamaquoddy Bay. It is interesting to see how the current passing through Letete Passage in the upper right of the figure breaks into a large eddy to the N and a second portion to the SW which follows the coastline of the central island.

This type of data demonstrates the utility of InSAR surface current mapping, but it is difficult to verify the accuracy of the results. Qualitatively, the data agree with expectations for tidal currents in the Bay of Fundy and the zero velocities measured for the land in both the Letete Passage and Cape Split scenes is encouraging, but a quantitative measurement of the velocity accuracy of the InSAR over water would be beneficial. To this end the NSC Frederick G. Creed made a series of point measurements of current during several survey lines in Scots Bay near Cape Split. The measurements were obtained by comparing the ship's expected velocity at constant engine revolutions to its actual velocity as measured from the real time differential GPS receiver on board. Since the currents are of similar magnitude and direction over the entire area sampled by the ship, the comparison was made between the average current vector measured by the ship (1.9 ± 0.6 m/s at $25 \pm 11^\circ$ East of true North) and the average current vector over the same area from Figure 2 (2.8 ± 0.3 m/s at $31 \pm 8^\circ$ East of true North). The directions of these two vectors agree but the magnitude discrepancy requires explanation. Taking the difference between each individual vector from the ship measurements and the corresponding vector from the InSAR measurements reveals a consistent difference of approximately 1.2 m/s at 41° E (i.e. very close to the direction of the current), which also suggests that the difference between the two sets of measurements is one of magnitude rather than of direction. It is necessary to refer to existing current models for the Bay of Fundy in order to resolve this apparent inconsistency. Although the current models have a very coarse spatial resolution they do show that at the mid flood tide the currents in the area measured by the ship (just SW of Cape Split) are changing direction very slowly, but growing in magnitude by 1 m/s to 2 m/s per hour. Both the ship based and InSAR based measurements occurred close to the mid flood tide, but each set of measurements occurred over a period of time and on different days. Taking the phase difference in the tide over the three day interval between the ship measurements and the InSAR measurements into account, the centre time for the InSAR measurements was approximately one hour later in the tidal cycle than the centre time for the ship based measurements. This means that the direction of the InSAR based measurements has been verified directly by an independent measurement and the magnitude by the combination of an independent measurement and the current models. It is also important to note that a magnitude error in the InSAR velocity measurements would translate into a directional error when the radial velocities from two passes were combined to get a single current vector, and this would frequently result in inconsistent currents around land areas such as Cape Split. This is something that is not present in these measurements.

SHIP AND WAKE SIGNATURES

In addition to providing ocean surface velocity information, the along-track InSAR can also provide velocity information about ships or wakes which may be present in the scene. There are several advantages to this. The first is in the detection of smaller ships which may not be significantly brighter than the background ocean clutter, and thus are difficult to distinguish from sea spikes. If these ships have a velocity component in the radial direction which is different from that of the surrounding ocean (which they will have unless they are drifting or moving exactly parallel to the aircraft track) then they will exhibit contrast from the ocean clutter in the velocity image even when the contrast in the magnitude image is minimal. The second is that the radial velocity component of any ship can be used to estimate its true velocity if its direction of travel can be determined either from its shape in the radar image or from its wake. The third advantage is that the detection of the wake itself may be improved, since it will also have a radial component to its velocity.

Figure 5 is a typical example of an InSAR magnitude scene showing two large, rapidly moving military vessels on the left and a much smaller fishing vessel with its nets deployed at the bottom of the image near the centre. This image was obtained on June 23, 1995 during the MARCOT '95 trials off the coast of Nova Scotia. The image is in slant range coordinates rather than UTM coordinates (there was a GPS failure during this mission) and nadir is at the top of the image. Figure 6 is a velocity image of exactly the same scene. The horizontal banding is caused by a poor phase calibration across the swath due to there being no suitable land area nearby to provide a phase calibration target. This should not affect the ships, however, since they are not in the portions of the swath where banding was a problem. The three ships and the wakes of the two larger ships are easily visible in the velocity image, and the fishing vessel is more easily detected than in the magnitude image, as predicted. All three vessels appear dark because the velocity image has been stretched to highlight moving targets. The orientation of the fishing vessel is not apparent, however, and its wake is not visible so its precise velocity can not be determined. Better results were obtained for the two military vessels. Using their wakes to establish headings on the ocean surface and the imaging geometry to project ocean surface motion into the radial direction, it is possible to determine that both vessels are traveling at 12 knots with a heading of 310° East of true North.

One additional feature of the InSAR velocity image shown in Figure 6 is the short horizontal line near the right of the image. This is also visible in the magnitude image, but it is more easily detected in the velocity image. This suggests that it represents either a small, highly defocused point target or a short, single arm wake, both of which could have significant radial velocities combined with small RCS. There was a radio controlled sonar dolphin operating ahead of the ships at this time. It is a small target which remains mostly below the water surface, but moves rapidly enough to create a visible wake, so it is the most likely cause of the unusual signature.

DETECTING SUBSURFACE FEATURES

On June 2, 1994 the CCRS InSAR flew a long flight line over the Bay of Fundy (Line 2, Pass 1) approximately two hours after low tide. Since the water depths were relatively low while the currents had already become large, this was an ideal time to detect underwater phenomena through their modulation of the currents flowing over them. A large number of objects were observed in both the magnitude and velocity images which could be related to known subsurface features. One of the most interesting was the Scots Bay dune field (See Figure 1(a)). This dune field lies SW of Cape Split and is composed of asymmetric dunes, with wavelengths ranging from 50 m to 500 m. The crests of the dunes lie between 10 m and 50 m below the low water mark and the average dune height varies from 4 m to 8m.

Figure 7 shows a sonar derived depth map (obtained by the NSC *Frederick G. Creed* over a twelve hour period on June 2, 1994) of the Scots Bay dune field in UTM coordinates, with lighter colours representing deeper depths below the WGS-84 reference ellipsoid. The beginning of the trench heading past Cape Split which was mentioned in Section 3 is visible in the top right of the image. This figure clearly shows how the dune field is divided by a central ridge into a larger, shallower Eastern portion and a smaller, deeper Western portion. It also shows that the dunes vary significantly in size, shape and depth, so a simple current model will be unlikely to properly describe the flow over the dunes. Despite this, Figure 8 shows a remarkable correspondence between the surface features observed by the along-track InSAR and the bottom features observed by the sonar. Figure 8(a) combines the magnitude of the interferogram as intensity with the radial velocity derived from the interferogram as colour. In this case the radial direction is 17.7^0 West of true North and the colour wheel uses green for positive currents, yellow for zero and red for negative currents. The minimum and maximum velocities observed in the image are -0.9 m/s and 1.5 m/s respectively. Figure 8(b) shows a simulated sun-illuminated image of the dune field derived from the sonar depth map of Figure 7. The central ridge and many of the larger dunes are visible both as intensity and colour modulations in Figure 8(a), suggesting that the changes in the Bragg scattering at the water surface which produce the intensity modulations are caused by velocity variations as the water passes over dunes of varying heights.

This result is predicted by theory such as that discussed by [van der Kooij et al., 1995], in which Bragg scattering variations at the surface of water passing over a uniform dune field are related to velocity variations defined by:

$$v_{par} = C_{par}, \qquad v_{per} = \frac{C_{per}}{h} \qquad (2)$$

where v_{par} is the surface velocity parallel to the crest of the sand dune, v_{per} is the surface velocity perpendicular to the dune crest, and h is the water depth. C_{par} and C_{per} are constants. From these equations, it is possible, in principle, to calculate the height to depth ratio of the dunes from velocity modulations such as those shown in Figure 8(a). In this particular case of InSAR measurements of the Scots Bay dune field, however, the model is inadequate. One reason is that the presence of the central ridge and the wide variety of dune orientations and sizes makes the hydrodynamics too complex for this model. Another is that the InSAR was only measuring the radial component of the velocity, and thus it was not possible to determine the true surface velocity vector field. In the later passes where perpendicular flight lines were used to create a full current vector map, the conditions for ideal imaging of the dune field were no longer present, probably because of the different aircraft track angles (with respect to the wind direction) used in these later flights.

Although the depth could not be directly extracted from the InSAR image, transects through the image are instructive. Figures 9(a), (b) and (c) respectively show plots of depth from the sonar map, InSAR magnitude modulation (in dB), and radial velocity (in m/s) versus distance along transects A, B, and C, which are plotted on an interferogram magnitude image of the Scots Bay dune field in Figure 9(d). Since both the InSAR image and the sonar map were in UTM coordinates it was possible to extract the values corresponding to the location of each transect from both data sets. A conversion from the WGS-84 ellipsoid to the mean tidal height at the time of the InSAR overpass was then used to get the true depth below the surface of the water. In all three cases, there is a strong correlation between depth, intensity and velocity modulations. The general trend is that the intensity is brighter where the water is deeper and the radial velocity is lower, but this should not be taken as an absolute rule since only one component of the velocity is being measured. Figure 9(a) shows that depth modulations of as little as 3-4 m can be detected in both the InSAR velocity and magnitude images even at depths below 30 m. Figure 9(b) demonstrates that even the slow depth change across the central ridge with a final depth below 40 m results in large changes in the InSAR image. Finally, Figure 9(c) shows how the depth modulations in the shallower part of the dune field can result in magnitude modulations greater than 10 dB and radial velocity modulations of 1.0 m/s. Taken together, these transects provide convincing evidence that the along-track InSAR can detect changes in the bottom topography of only a few meters at water depths of 30 m and beyond. Even though the absolute depth can not be determined from a single radial velocity component, it is sufficient to determine the precise location of a dunefield and the shape of the major dunes. Under other imaging conditions (e.g. lower ambient currents or lower winds so that the backscatter from the water was very low), the results might not be as impressive, but subsurface features have been detected in many other InSAR scenes. The Scots Bay dune field was used as a test case because of the availability of a temporally coincident, geographically registered sonar depth map.

In addition to detecting the presence of underwater topographic features, along track InSAR can also provide insight into the imaging mechanism by which these features become visible in conventional SAR imagery. After using the simple flow model shown in Equation 2 to calculate the dependence of the surface velocity modulation on the depth modulation, an imaging model must be developed to relate the velocity modulations to radar cross section modulations (e.g. [Alpers and Hennings, 1984], [van der Kooij et al., 1995], [Romeiser, 1996]). Verification of that imaging model is then obtained by comparing the intensity modulations in the radar image with the depth modulations from a sonar map or hydrographic chart. If the current flow is non-laminar or the dunes have unusual shapes, however, then a model which accurately relates depth modulation to current modulation will be extremely complex and it will be very difficult to determine the validity of the radar imaging model. The along track InSAR provides a way of measuring the currents at the identical time, position and resolution scale as the radar cross section, thus allowing the relationship between surface current modulation and RCS modulation to be studied directly. A demonstration of this technique is shown in Figure 10. A single transect through the dune field in the radial direction was chosen such that it was perpendicular to three major dune crests. The basic model from [Alpers and Hennings, 1984] was used to relate modulations in the radar cross section, σ , to modulations in the radial component of the surface current, U_x :

$$\frac{\partial \sigma(x)}{\sigma_0} = -\frac{4+\Gamma}{\mu}\frac{\partial U_x(x)}{\partial x} \quad \text{where} \quad \Gamma = \frac{1+3k^2\tau\ /g\rho}{k^2\tau\ /g\rho} \qquad (3)$$

Here s_0 is the mean RCS, k, the Bragg wavenumber, t, the surface tension, g, the acceleration due to gravity, m, the relaxation rate, and r, the density of water. For the Line 2, Pass 1 case from June 2, 1994, the radial direction was almost perpendicular to the surface wind (as measured on board the NSC *Frederick G. Creed*) and this made a precise determination of m impossible. Setting it to unity results in Figure 10(a), where the left hand side of Equation 3 has been plotted as Normalized RCS and the right hand side as (4+G) dU/dx. There is a convincing correlation between the two modulations. Cross-correlation analysis indicates that a phase shift of approximately 25m produces the best correlation, as shown in Figure 10(b). This highlights the ability of the along track InSAR to provide insight into ocean imaging without the need to use current flow models.

The InSAR detected several known subsurface features in the Bay of Fundy, including the Cape d'Or - Cape Spencer dune field and a large shoal off Cape d'Or. In most cases, the objects appeared in both the magnitude and velocity images, but in some cases debris on the water, changes in local winds, or other non-topographic factors made it difficult to observe a given feature in the magnitude image. The velocity image was less likely to be degraded by these effects. The shoal off Cape d'Or, for instance, appeared in the magnitude image as a bright line, similar to those observed near many sharp coastal features due to local water turbulence, but in the velocity image it could clearly be detected as a sharp edge between two bands of water flowing in opposite directions (i.e. a local shear zone formed along the shoal). The northernmost part of this feature can be seen in the bottom right corner of Figure 11. One of the most exciting features imaged was a small dune field SW of Advocate Harbour, which is also shown in Figure 11. This combined magnitude and velocity image uses the same velocity colour wheel as was used previously in Figure 8(a). The dune field is not as clear as the Scots Bay dune field in that previous image, but it is definitely visible. This dune field, however, was not mapped by the NSC *Frederick G. Creed* because it did not exist on any previous maps and thus was not included in the ship's sailing plan. In this case the airborne InSAR was able to detect an underwater feature which had been missed by previous ocean based surveys. Verification of the location of the dune field was provided by local fisherman who were familiar with the shoals and dunes in the immediate vicinity of Advocate Harbour, and a CHS survey of the dune field has now been scheduled for 1996. This is a perfect example of how the wide area coverage of the airborne InSAR can be used to detect subsurface features which can then be more precisely mapped using conventional sonar techniques.

Since many of the subsurface features cause both velocity and magnitude modulations, a comparison was made between the information which can be obtained using an airborne along-track InSAR and that which can be obtained using magnitude images from a satellite based SAR. The Earth Remote Sensing (ERS-1) satellite made sixteen overflights of the Bay of Fundy between April 21, 1994 and September 19, 1994. This European Space Agency satellite carries a C-band VV polarized SAR which could potentially detect some of the underwater features in the area. The state of the tide and the wind speed and direction were determined for each of the sixteen times corresponding to ERS-1 overpasses. From these data, August 11 and 13 were determined to be the two most likely candidates for detection of subsurface features. SAR Geo-referenced Fine (SGF) images from all the available passes were examined for evidence of subsurface features. Most showed no such evidence, either due to high winds (no subsurface features were detected in any overpass with wind speeds greater than 12 knots) or due to the tidal conditions being inappropriate. In a few passes some of the dune fields previously detected by the InSAR were observed, but the intensity modulations were small, and if the location of the Scots Bay dune field had not already been known, it would have been very difficult to identify it. Figure 12 shows the two subscenes from the ERS-1 imagery which best display the Scots Bay dune field. In Figure 12(a), acquired on an ascending pass on June 15 approximately two hours after low tide, the ridge line along the centre of the dunefield is visible as the dividing line between regions of brighter and darker water in the upper left of the image. In Figure 12(b), acquired from a descending pass on August 13 (also two hours after low tide), the shallower portion of the dunefield is visible as a dark region to the left of Cape Split. Individual dunes can not be seen in either of these images and it is difficult to distinguish the magnitude modulation caused by the presence of the dunes from the magnitude modulations in other parts of the image caused by naturally occurring slicks and local wind speed variations.

Only one ERS-1 overflight of all those examined showed significant magnitude modulations at the location of a subsurface feature. This was an ascending pass on August 11 which occurred 3.5 hours after low tide and showed modulations in the vicinity of a group of very large, isolated dunes SW of Ile Haute which form part of the Margaretsville dune field. These dunes are much larger both in terms of wavelength and depth modulation than the Scots Bay or Advocate Harbour dunes, which explains why they were more easily visible in the relatively low resolution satellite image, as shown in Figure 13. Since these three subscenes represent the best available ERS-1 images of dunes in the Bay of Fundy over a five month period, it appears that this satellite sensor is far less suitable than the airborne InSAR for mapping the type of subsurface features found in the Bay of Fundy.

CONCLUSIONS

This study has affirmed the utility of the CCRS airborne along-track InSAR as a tool for studying ocean surface features. It can produce high resolution, geocoded, calibrated velocity images which can be combined to produce current velocity maps for currents which are stable over the time between passes (approximately twenty minutes under typical flight circumstances). Since there is currently no simple way of producing a high resolution current map over a large area, along-track InSAR may be a useful tool for examining the current patterns in river deltas, harbours, or other areas where a detailed knowledge of the currents will assist in predicting safe shipping paths or in environmental monitoring of erosion and sedimentation processes.

Under favourable imaging conditions, the along-track InSAR can also be used to detect subsurface features. The absolute depth to depth modulation ratio of detectable features for the Scots Bay dune field in the Bay of Fundy was limited to approximately 10, but the ambient current and wind conditions are expected to significantly affect this value, so it is difficult to use this number to predict results in other areas. This means that ship based sonar surveys can produce more detailed maps of subsurface features than can airborne InSAR surveys. Ship based surveys, however, are very time consuming (approximately

12 hours of sonar imaging time was required for the Scots Bay dune field versus approximately 1 minute for the InSAR image). They typically focus only on small areas where subsurface features are already known to exist. The airborne InSAR, by contrast, can easily cover thousands of square kilometers in a single day and can thus detect features which were previously unmapped, such as the dune field SW of Advocate Harbour. The survey ships can then be called in to produce accurate depth maps of the new subsurface features detected by the InSAR.

Satellite imagery can also show evidence of subsurface features. The detectability of subsurface features in the Bay of Fundy was relatively poor, however, when comparing ERS-1 imagery to InSAR imagery of the same areas. Other satellites with different resolutions and polarizations should be investigated in the future. The Canadian RADARSAT would be particularly interesting to compare with the magnitude images from the along-track InSAR, since both of these radars operate in HH polarization at C-band.

Along-track InSAR imagery also improves the detectability of moving targets on the surface of water (such as ships or certain types of wakes) because they can have high contrast in the velocity image even if they have very low contrast in the magnitude image. If the orientation of a ship can be determined from its shape in the image or from its wake, then a single radial velocity measurement also allows a full determination of the ship's velocity on the surface of the ocean.

The CCRS along-track InSAR thus has the potential to provide useful information about ocean currents, ships and wakes, and subsurface features. It has proved this capability in multiple missions between 1994 and 1996, and hopefully will do so again in the future.

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Figure Captions:

Fig. 1(a) - Map of the Bay of Fundy near Cape Split and the Minas Basin, showing the location of the Scots Bay dune field and of Cape d’Or.

Fig. 1(b) **-** Map of the islands separating Passamaquoddy Bay from the Bay of Fundy. The locations of both Letete Passage and Little Letete Passage are shown.

Fig. 2 **-** Velocity map of the surface currents around Cape Split in the Bay of Fundy during a flood tide, three hours before peak tide. The blue vectors show the magnitude and direction of the average velocity of 250m by 250m regions centred at the starting point of each vector. Colour represents velocity from black (0 m/s) through red, orange, yellow and finally white (5 m/s). This image was created by combining data from two flights over the area by the CCRS along-track InSAR on June 2, 1994. North is towards the top of the figure and the total area shown is 10.5 km by 10.5 km.

Fig. 3 **-** Magnified velocity map from a portion of Figure 2. In this case the velocity vectors represent averaged regions of 40 m by 40 m.

Fig. 4 **-** A 5.0 km by 5.0 km InSAR magnitude image of the islands near the Letete Passage at the entrance to Passamaquoddy Bay on June 24, 1995. The vectors (shown only for areas where the radar backscatter was sufficiently high to get coherent phase in both this image and a perpendicular crossing pass) represent the magnitude and direction of the average velocity of 120 m by 120 m regions.

Fig. 5 **-** Slant range (nadir is at the top of the figure) InSAR magnitude image of two military vessels (left centre) and a fishing boat with its nets deployed (bottom centre). The wakes of the military vessels are clearly visible. This image was acquired during the MARCOT ‘95 trials on June 23, 1995.

Fig. 6 - Velocity image corresponding to the magnitude image of Figure 5. The three original ships are clearly visible, as is a short horizontal line, which may be the signature of a sonar dolphin, to the right of the military vessels.

Fig. 7 - Depth map of the Scots Bay dune field in UTM coordinates (North towards the top of the image) produced by the scanning sonar aboard the NSC Frederick G. Creed on June 2, 1994. Lighter colours represent deeper depths below the WGS-84 ellipsoid, ranging from 17m to 137m.

Fig. 8(a) - Combined magnitude (as intensity) and velocity (as colour) InSAR image of the Scots Bay dune field. The colour wheel ranges from green (positive velocity towards 17.7^0 W of true N) to yellow (zero) and red (negative velocity).

Fig. 8(b) - Simulated sun-illuminated image derived from the sonar depth map of Figure 7. Note that all the large features of the dune field shown here have corresponding surface features in Figure 8(a).

Fig. 9(a) - Depth (in meters) below the surface of the water from the sonar depth map, magnitude modulation (in dB), and radial velocity (in m/s) from the InSAR image as a function of distance along transect A shown in Figure 9(d).

Fig. 9(b) - Depth (in meters) below the surface of the water from the sonar depth map, magnitude modulation (in dB), and radial velocity (in m/s) from the InSAR image as a function of distance along transect B shown in Figure 9(d).

Fig. 9(c) - Depth (in meters) below the surface of the water from the sonar depth map, magnitude modulation (in dB), and radial velocity (in m/s) from the InSAR image as a function of distance along transect C shown in Figure 9(d).

Fig. 9(d) - InSAR magnitude image of the Scots Bay dune field showing three transects through the dunes.

Fig. 10(a) - Plot of normalized RCS modulation and surface velocity modulation, (4+G) dU/dx, as a function of distance along a transect through the Scots Bay dune field in the InSAR radial direction.

Fig. 10(b) - Identical to Fig. 10(a), except that the RCS modulation has been phase shifted +25 m along the transect.

Fig. 11 - Combined InSAR magnitude and velocity image of a previously uncharted dune field SW of Advocate Harbour. The velocity to colour mapping is the same as that in Figure 8(a).

Fig. 12(a) - Subscene from an ERS-1 SGF image (ascending pass on June 15, 1994) showing Cape Split. The central ridge of the Scots Bay dune field appears as the dividing line between two regions of light and dark water just left of Cape Split.

Fig. 12(b) - Subscene from an ERS-1 SGF image (descending pass on August 13, 1994) showing the shallower part of the Scots Bay dune field as a slightly darker region left of Cape Split.

Fig. 13 - Subscene from an ERS-1 SGF image (ascending pass on August 11, 1994) showing Ile Haute (top right) and a series of periodic intensity modulations (below and left of Ile Haute) near part of the Margaretsville dune field.