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**Ice Jam Detection and Flood Monitoring
Using Airborne Synthetic Aperture Radar:
Saint John River, New Brunswick, 1987**

by

PETER FARRIS-MANNING

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Master of Arts

Department of Geography

Carleton University
Ottawa, Ontario
December, 1991

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**Ice Jam Detection and Flood Monitoring Using
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submitted by
Peter J. Farris-Manning
in partial fulfilment of the requirements for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography

**Carleton University
1991**

Abstract

The Saint John River flood of April, 1987 was a dramatic example of ice jam flooding. At the peak of the flood, the Canada Centre for Remote Sensing acquired synthetic aperture radar (SAR) imagery along most of the river's course. This study contributes to the investigation of the potential of SAR in ice jam detection and flood monitoring. Software is developed for digital image geocoding and display on a personal computer, thus facilitating the comparison of SAR imagery with other georeferenced spatial data.

It is shown that synthetic aperture radar offers a unique capability of providing all-weather, ice jam detection and flood monitoring. It is concluded that the software required for ice jam detection and flood monitoring can be successfully integrated to provide the geographic information desired.

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Contents

1	Overview	1
1.1	Existing Research	2
1.2	Data Acquisition	4
1.3	Methodology	7
1.4	Software/Hardware Requirements	8
2	The Nature of Ice Jam Floods	9
2.1	Human Responses to the Flood Hazard	11
2.2	Saint John River Flood, April 1987	13
2.2.1	Radar Imagery of the Flood	15
2.2.2	Gagetown Island Study Area	18
3	Remote Sensing of Ice Jam Floods	22
3.1	Basic Principles of Radar	25
3.2	Sources of Geometric and Radiometric Distortion	28
3.2.1	Slant Range Scale Distortion	28
3.2.2	Topographic Effects	28
3.2.3	Speckle	29
3.2.4	Motion Compensation System	29
3.2.5	Sensitivity Time Control (STC)	30

4	SAR Image Geocoding	31
4.1	Correction of Geometric Distortion	31
4.1.1	Deterministic Errors	33
4.1.2	Skewness	35
4.1.3	Rotation	35
4.1.4	Offset	37
4.1.5	Overall Model	38
4.2	Geometric Correction Software	38
4.3	Results for Gagetown Imagery	39
4.4	Image Resampling	41
5	Radiometric Processing	43
5.1	Filtering	45
6	Comparison of Data Sets	48
6.1	Ice Jam Dynamics	49
6.2	Flooded vs. Non-flooded Imagery	52
6.3	Cultural Feature Masking	55
6.4	Airphotos vs. Radar Imagery	57
6.5	Detection of Ice Jams and Flooding	59
7	Conclusions	61
7.1	Approaches to Image Interpretation	63
A	Summary of Software	65
B	Geometric Correction Software	66

List of Tables

1.1	Summary of Imagery	6
4.1	Design Parameters for RTSP Pixel Resolution and Spacing	32
4.2	Example of LSTSQR.DAT Output	40
4.3	Gross Geometric Distortions in the Real-Time Data	41
6.1	Floe positions between passes	51

List of Figures

1.1	Map of Study Area	5
2.1	Example Radar Scene	17
4.1	Image Recording Configuration	34
4.2	Image Skewness	35
4.3	Rotation from the Image to UTM Reference Frame	36
5.1	Image Histogram Computed by SARDM1	44
5.2	Lee-filter and Sobel Edge Filter Comparison	47
6.1	Ice Jam Dynamics	50
6.2	Ice Jam Change Detection	53
6.3	X-band and C-band Comparison	54
6.4	Cultural Feature Masking	56
6.5	Airphotos vs. Radar Imagery	58

Chapter 1

Overview

The Saint John River flood of April, 1987 was one of the most dramatic examples of ice jam flooding in recent Canadian history. Huge ice floes smashed down a railway bridge at Perth-Andover, and the flood levels drove hundreds of residents from their homes. New Brunswick's climate is such that rivers routinely freeze over during the winter months and severe flooding due to ice jams often occurs during the spring thaw and break-up, quite often resulting in damage to cultural features close to the river's edge. New Brunswick has a long history of flooding, with the first recorded flood occurring near Jemseg in 1696 (Environment Canada, 1984, p. 1). Ice jams tend to occur where there are constrictions in the channel such as at bridges, sharp bends, or in gorges. Shallow sections of the river or areas where the gradient levels out are also prone to ice jamming. The ice jams are often short-lived and might conceivably occur at any time in the break up season and at any point in a long curvilinear corridor, thus making ground-based monitoring quite difficult (Ministry of Natural Resources, 1984, p. 7). Remote sensing is particularly suited to observing such transient phenomena since large areas may be monitored over a relatively short period of time.

Given that the conditions leading up to ice jam flooding might typically be cloudy periods, there is a significant possibility that the flooded area will be largely

obscured by cloud cover at the time of greatest interest. Microwave radar offers the unique advantage of being able to sense through cloud cover and it is this property in particular which suggests the applicability of synthetic aperture radar (SAR) to flood studies.¹

This study contributes to the investigation of the potential of SAR in ice jam detection and flood monitoring. Software is developed for digital image geocoding and display on a personal computer, thus facilitating the comparison of SAR imagery with other georeferenced spatial data.

1.1 Existing Research

Remote sensing has received a lot of attention from geographers as a tool for terrain reconnaissance and resource monitoring, along with many other applications. The synoptic viewpoint afforded by airborne and spaceborne sensors is particularly valuable in countries such as Canada where there are vast areas for surveillance. Microwaves are capable, to a large degree, of penetrating cloud cover which is an important limiting factor in the use of Landsat Multispectral Scanner Subsystem (MSS) data (or other scanners using the visible spectrum) for flood monitoring, since the most important time period to image is likely to be preempted by cloud cover. This limitation would be more severe in a monsoon climate where flooding typically results from long term precipitation.

There may, on the other hand, be limitations inherent in SAR data which are not present in data from other sensors. One must be careful, therefore, when considering the advantages of using a particular sensor over another, that comparable capabilities are afforded by either sensor. It should be recognized that a radar image is not the equivalent of an aerial photograph since the energy being detected is of a different wavelength and is influenced by different characteristics of the target. It will be pointed out, therefore, that different sensors offer different *views* of the flooded area based on the nature of their respective imaging processes and sensitiv-

¹Synthetic aperture radar is a variety of microwave radar.

ities. And some characteristics are more important to some fields of analysis than others.

With respect to the process of image analysis, in this case flood monitoring and ice jam detection, any number of possible approaches may be adopted, ranging from a fully manual, visual interpretation to a more automated, quantitative interpretation. Imagery stored in a digital format lends itself very well to automated analysis, but it may not always be a desirable approach, or even a very expedient one when one factors in the difficulties involved in image registration. One of the objectives of this thesis will be to assess these two different approaches to the interpretation of airborne SAR imagery, since SAR has the potential to play an increasingly important role in flood monitoring in the future.

The use of remote sensing for ice jam detection is desirable in light of the transient nature of ice jams. The majority of research into the applications of radar in monitoring ice, however, has been centred on sea ice due to the international interest in sea ice. In fact, in 1976, Parashar (p.9) claimed that there were *no* radar measurements of river ice.

Perhaps research should be pursued on radar sensitivity to river ice structure so that a multi-temporal analysis around the time of spring break-up might yield a model for predicting ice jam flooding. That is not the intent of this work. This work might provide a basis for studies of causality, but focuses on assessing the potential of SAR in detecting existing ice jams.

A key issue in establishing the use of SAR for flood monitoring is the accuracy with which it is possible to map the temporal changes in land/water boundaries and monitor the intersection of flooded areas with cultural features. The superimposition of multiple data sets of different formats is a significant challenge to geographers and one which perhaps will only be met by the adoption of automated techniques. The development of geographic information systems will likely ease this task in the future.

1.2 Data Acquisition

The data set used for this study was acquired during the Saint John River Flood of April, 1987 by the Canada Centre for Remote Sensing (CCRS) for the Water Resources Branch of the New Brunswick Department of the Environment with a C-band synthetic aperture radar (SAR) on board the CCRS Convair-580 aircraft. The data acquisition took place on April 3rd, 1987. The data set includes imagery of most of the Saint John River valley from Perth-Andover to Saint John Harbour in four radar swaths. Twenty five square kilometres of data were extracted from the area surrounding Gagetown Island centred at approximately $N45^{\circ}47'$ latitude and $W66^{\circ}08'$ longitude. This will translate into a resampled image area of 1000 by 1000 pixels at 5 m pixel spacing, which is roughly consistent with the radar resolution in narrow swath mode (Livingstone et al., 1987, p. 1). The map in Figure 1.1 shows the location of the study area within New Brunswick as well as significant features inside of the study area. ²

The study area was chosen primarily because of the intense flood dynamics present in the scene, identified by a visual analysis of the real time imagery (refer to Figure 2.1). A large ice jam is present at the bend of the river near Lower Jemseg, flooding is evident on both sides of the river and on much of Gagetown Island itself. An interesting flooded forest effect is evident on the island and other flooded areas. And lastly, but importantly, the area was imaged on two successive lines approximately 20 minutes apart and significant ice motion can be seen to have taken place in the jam during that time.

The imagery used for this study was composed of elements from various sources. A summary is presented in Table 1.1. The two C-band SAR images were from the two flight lines discussed above and were part of the data set collected by CCRS. Three X-band images were made available by MacDonald Dettweiler Technologies (MDA), two in narrow swath mode and one in wide swath mode. The narrow swath images did not fully overlap the study area and hence were not used. The purpose

²The map was adapted from the National Geographic Atlas of the World, 4th edition, p. 58 and a 1:50000 topographic map of the Grand Lake area, New Brunswick (21G/16).

Figure 1.1: Map of Study Area

Table 1.1: Summary of Imagery

Image	Source	Description
CCRS-1	Canada Centre for Remote Sensing	Pass 3, C-band SAR, narrow swath
CCRS-2	Canada Centre for Remote Sensing	Pass 4, C-band SAR, narrow swath
MDA-1	MacDonald Dettweiler Technologies Ltd.	Pass 1, X-band SAR, narrow swath
MDA-2	MacDonald Dettweiler Technologies Ltd.	Pass 2, X-band SAR, narrow swath
MDA-3	MacDonald Dettweiler Technologies Ltd.	Pass 3, X-band SAR, wide swath
MAP	1:50000 flood risk map, New Brunswick Department of the Environment, Water Resources Branch, April 1981	scanned map segment
PHOTO	1:50000 air photo taken in June, 1979	scanned air photo
RIVER	1:50000 flood risk map, New Brunswick Department of the Environment, Water Resources Branch, April 1981	manually digitized river boundaries converted to a raster format with re- gion inside the river boundaries filled with a constant value --- useful for iso- lating the river from other image fea- tures
LAND	1:50000 flood risk map, New Brunswick Department of the Environment, Water Resources Branch, April 1981	manually digitized river boundaries converted to a raster format with land regions filled with a constant value — useful for isolating the land from other image features

of using the X-band data was twofold. It provided a comparison of microwave sensitivity at a second frequency and also provided an image of the river approximately two months before the flood and hence the river was completely ice covered.

In addition to the radar imagery, a digitized 1:50000 flood risk map from the New Brunswick Department of the Environment (Water Resources Branch, April 1981) was used to show where the normal river boundary exists in relation to the radar imagery as well as to show cultural features which might be at risk of flooding. The land water boundary was also manually digitized so that land and river *masks* could be generated and combined with other images to allow analysis of land or water features in isolation. Finally, a 1:50000 air photo taken in June, 1979 was scanned to provide a comparison of microwave imagery with visible light photography.

In addition to the imagery data used in this study, some field research was carried out at the end of August, 1988. This is discussed in more detail in section 2.2.2.

1.3 Methodology

The data was resampled to a Universal Transverse Mercator (UTM) frame of reference for ease of comparison with map data and other UTM referenced images. The method used to geocode the image illustrates the different kinds of geometric distortions and how they may be removed. A straightforward rotation, scaling, and skew correction based on a set of ground control points, ignoring topographic effects, is used. Distortion due to topographic effects can be ignored in this case since the local relief in the area of interest is only 25 feet. The issue of topography, of course, needs consideration in order to assess the applicability of SAR image analysis to flood monitoring in mountainous terrain, but that is not the intent of this work. A nearest-neighbour resampling algorithm was used rather than performing any sub-pixel interpolation since that degree of accuracy was not deemed necessary.

Land/water boundaries were digitized from a topographic map of the study area and converted to the same reference frame as the imagery. Having done this, it is possible to estimate the flooded area, as well as to overlay significant cultural features such as roads on the image, yielding automated detection of flooded cultural

features.

Discrimination between ice and water, or land and water, was based on radiometric levels. The ice and water discrimination was restricted to the normal river boundary as specified by the topographic map. This precludes the detection of fast ice beyond the normal river's edge, but such an analysis was beyond the scope of this study.

1.4 Software/Hardware Requirements

Most of the computerized digital analysis was accomplished using a personal computer (IBM compatible 386 with a 387 coprocessor) and displayed on a colour graphics monitor capable of displaying 256 colours at a resolution of 1024 by 768. The study area was chosen using the Knudsen Engineering ALICE Multisensor Display Subsystem (MSD). This allows quick display of a high-density data tape as recorded onboard the aircraft. Topographic map data were digitized using a Summagraphics MM1812 digitizing tablet resident on a DEC PDP-11 system. Digital SAR data was transcribed from tape to disk using a microVAX system.

Chapter 2

The Nature of Ice Jam Floods

At the conceptual level, the phenomenon of flooding is quite readily understood. One may recollect images of flood events from personal experience which quite vividly portray the notion of flooding. The complexity and variation in the outward manifestations of flooding, however, make its rigorous definition elusive.

In conceptual terms, one may think of flooding as the consequence of water rising beyond a river's banks. This sort of definition, however, is problematic due to the fact that the banks of a river vary in elevation throughout its course. There can, therefore, be no single level above which the river is in flood and below which it is not in flood.

Ward (1978, p. 5) defines a flood as "a body of water which rises to overflow land which is not normally submerged." This definition is perhaps more accurate than the first one in that it encompasses floods caused by water bodies other than rivers (oceans, for instance) and it refers explicitly to land not 'normally' under water.

The Penguin Dictionary of Physical Geography (1984, p. 197) defines a flood as "the inundation by water of any land area not normally covered with water owing to a relatively rapid change of the level of the particular water body in question." The rapidity of inundation attributes an element of unexpectedness to the phenomenon and, where human civilization is affected, this becomes viewed as a hazard. In contrast to this negative view, flooding in some circumstances is viewed as a natural phenomenon which is often beneficial and even essential for proper irrigation in agricultural areas.

The intent here is to show the non-trivial nature of a formal definition of flooding in contrast to the popular intuitive conception of flooding. Rather than being concerned with deriving a formal definition, the objective here is to develop an awareness of the plethora of causes and outward manifestations of what has often been reduced to the single term "flooding".

The flooding phenomenon is often intensified or complicated in colder climates when the precipitation takes the form of snow or when ice forms on the surface of rivers and lakes. This thesis is concerned with a particular form of flooding known as *ice jam* flooding. Rivers in colder climates often freeze over during the winter months resulting in severe flooding during the spring thaw and break-up due to ice jam effects. The World Meteorological Organization (WMO) defines an ice jam as "an accumulation of broken river ice or sea ice caught in a narrow channel." (1970, p. 11)

Ice jam floods often occur where there are constriction points in the channel such as at bridges, sharp bends, or in gorges. Sections of the river where the gradient levels out or where there are shallow sections are also prone to ice jamming. Ward (1978, p. 36) explains that the water level behind a jam rises, often quite rapidly, until the obstruction eventually gives way, releasing "great volumes of water and debris into the downstream channel". Floods can occur upstream of an ice jam due to the water backing up, or downstream after the jam bursts. Mitchell (1978, p. 25) points out that the build-up of massive ice-jams is less likely when the river's lower reaches thaw earlier than its upper reaches. The worst scenario is when ice break up occurs first in the river's headwaters and moves progressively downstream (Prowse, 1989, p. 24).

Hoyt (1955, p. 31) describes the physical process of ice jam flooding in the following way:

Ice break-up is normally preceded by a warm spell that sends melt-water into cracks in the ice. The once solid ice is transformed into a honeycomb structure of long crystals normal to the surface. It is now structurally weak even though visually it still looks solid. Snowmelt

swells the streams, and the ice is broken from its banks. Most of the ice will turn to slush.

If the thaw develops suddenly, however, the ice will not be 'primed' for easy break-up. The ice ruptures from the swelling waters and floats in cakes or sheets. The loosened ice may become stuck in constrictions like narrows, bends, or bridges, forming an ice dam. The jam will hold until the force of the backwater breaks the jam. The rapid release of the impounded water results in downstream flooding.

Depending on the thickness of ice and the rate at which melting takes place, river ice may break up in stages or a general disintegration may take place. Without a general disintegration, there is a greater chance that ice may jam in several places as it encounters a solid ice cover at various points along the river's course (Ontario Ministry of Natural Resources, 1984, p. 13).

2.1 Human Responses to the Flood Hazard

The phenomenon of flooding can be a dramatic point of interaction between humans and their environment. In this section the societal implications of flooding and the reasons behind the desire for ongoing flood monitoring systems will be pointed out.

The potential danger of floods has led societies to attempt to control or reduce the flood hazard and, indeed, contemporary societies have been so successful in this control that they routinely harness the power of surging waters to their benefit. Dams have often been built on rivers with strong seasonal variations in discharge in attempts to regulate downstream flow, where important economic activities take place.

The economic implications of flood management as well as the implications of potential flood damage are considerable. They involve the costs of building embankments, floodwalls, reservoirs, and channel diversions if flood protection is desired. They involve the costs of afforestation, snow management, etc. if flood abatement is desired. In the event of a major flood, there are the costs of buildings, bridges,

roads, railways, land and crops destroyed, as well as the loss of productivity, losses of business and income, and sometimes loss of life. As well, there are the less tangible costs of human fear, anxiety, annoyance, distress, insecurity, and ill-health (Ward, 1978, p. 173).

It is interesting to note that human societies persistently inhabit flood-prone areas despite the recognized hazard associated with such behaviour. Mitchell (1978) suggests that this indicates that the benefits of a riverine location must surely outweigh the periodic costs incurred from flooding. The price paid for *security* on the floodplain downstream of a major water impoundment, however, often takes the form of further negative environmental consequences. The environmental impact of human intervention in river regimes can, in fact, be quite alarming. Although there is a long history of human response to the flood hazard, the phenomenon is still not fully understood. Ward (1978) maintains that to the general public, floods are often unexpected, inexplicable and always traumatic experiences.

Historically, human settlement of floodplains was dictated by considering, for example, the need in arid regions for moisture to grow crops, or the requirement of utilizing relatively level land in mountainous regions. While modern agricultural technology has relaxed these requirements somewhat, Ward (1978, p. 113) points out that indiscriminate floodplain development has continued "partly because of *geographic inertia* whereby existing settlements continue through peripheral accretion."

Measures may be taken to reduce the risk of damage due to flooding by estimating the nature and severity of future floods. In the design of dams, storm sewers, culverts, bridges, etc., engineers need information on flood magnitude and frequency. A fundamental question for design purposes concerns the *design flood* which is the "maximum flood against which protection is being designed" (Ward, 1978, p. 69). Various methods are available for estimating design floods, these methods basically falling into two categories: those which are *deterministically based*, and those which are *probabilistically based*. Deterministic methods attempt to relate precipitation to flood magnitude based on the nature of the drainage basin (Ward, 1978, p. 71). Probabilistic methods regard floods as "random streamflow events whose distribu-

tion can be identified and whose probability of occurrence during a given period of time can be calculated using standard statistical techniques" (Ward, 1978, p. 80).

Flood forecasting is generally intended for warning purposes and requires more immediate flood magnitude and timing information than is required for statistical flood prediction. Local governments, industrialists, farmers and the general public utilize flood forecasts so that appropriate evasive action may be taken in an attempt to reduce potential flood damage. Information on flood volume, depth, and duration is required.

2.2 Saint John River Flood, April 1987

This section describes the situation in and around April 3rd, 1987, the date of radar data acquisition. Information was gathered from local and national newspapers during the flood. The exact locations of the events mentioned will not be pinpointed on a map but the information will convey a sense of the kind of events which were occurring.

The two major areas where ice jams still existed on April 3rd were just south of Woodstock at Meductic and in the Jemseg-Grand Lake area. Water was also reported to be still covering the Trans-Canada Highway in the Mangerville-Sheffield-McGowan's Corner area (Water Levels Dropping, 1987, p. 3).

The problems with ice jam flood forecasting were made obvious in comments from spokespersons of the Saint John River Valley Flood Forecast Centre as the flood progressed. On the eve of one of the most devastating flood events in Perth-Andover, the Flood Forecast Centre could only report that no serious damage had yet occurred from minor ice jams, and stated that they expected the river levels to go higher depending on the rain (Llewellyn, 1987, p. 19). This is not to belittle the efforts of the Flood Forecasting Centre, but rather to point out the speed with which the river conditions changed, and the difficulty of human efforts to monitor that change on the ground.

The Emergency Measures Organization (EMO) spokesperson in Woodstock reported Thursday morning (April 2) that the Perth-Andover railway bridge had been

washed out and that over 1000 persons had fled their homes. Telephone contact with the community had been lost, and the EMO had been keeping in touch by radio. The second span of the Grafton side of the Upper Woodstock CPR railway bridge had been washed out on Wednesday (Benteau, 1987, p. 1). This had necessitated re-routing rail traffic en route to Fredericton or Saint John.

The RCMP awakened residents of Perth-Andover starting at 3 a.m. April 2nd to warn them of the flooding. The *Daily Gleaner* reported that some residents were sceptical when the warning was given but "that changed when the 290-metre-long train bridge crashed into the St. John River about 9:15 a.m." (Benteau, 1987, p. 1).

The bridge had been buckling under the strain of an ice jam and officials had hauled 17 boxcars onto the structure to use as ballast. Those cars, including 13 loaded with ammonium sulphate, diammonium phosphate... and potash, fell into the river along with the bridge (Benteau, 1987, p. 1).

The EMO maintained there was no danger to humans from the chemicals which were believed to be water soluble and toxic to fish (Benteau, 1987, p. 1). In Ottawa, April 3rd, Fisheries Minister Tom Siddon and Transport Minister John Crosbie criticized the decision to use the boxcars as ballast even though CP Rail knew of the contents of the cars (Story, 1987, p. A4). John Crosbie was later quoted as saying that if the cars begin leaking "the contents could harm the fish, but it is expected the waters will dilute them sufficiently so there won't be any harm caused" (Martin, 1987, p. 4). Municipal Affairs and Environment Minister Robert Jackson commented that the decision to place the cars on the bridge was a difficult one to make. It had been hoped that the "added weight of the cars, each weighing about 100 tonnes when empty, would counter the pressure placed on the bridge by the raging water and ice" (Water Levels Dropping, 1987, p. 3).

Environment Minister Robert Jackson declared a state of emergency for the Saint John River Valley on April 3rd. This provided municipalities with special powers which would enable them to combat the flooding. For instance, "under the Municipalities Act and existing city bylaws the mayor [of Fredericton] could

commandeer vehicles, people and private property and resources to fight the flood waters. He can also authorize spending without going to council" (Llewellyn, 1987, p. 17).

The mayor of Perth-Andover estimated one million dollars of damage to the Hotel-Dieu Hospital alone. The EMO reported flooding as high as the beds on the first floor. "Flooding wiped out the emergency and X-ray departments along with laboratories and the pharmacy" (Martin, 1987, p. A4). Residents were told not to move back into their houses until electricians had established that power could safely be reconnected. People whose wells were flooded were advised for a ten day period to boil their water as a precautionary measure (New Brunswick Floods Force Hundreds to Flee Along Saint John River, 1987, p. A1). Perhaps the most ironic effect of the flood was the damage caused to Woodstock's pumping station which resulted in a water shortage. Water had to be shipped in by truck (Water Levels Dropping, 1987, p. 3).

2.2.1 Radar Imagery of the Flood

During the flood, the Water Resources Branch of the New Brunswick Department of the Environment contacted the Canada Centre for Remote Sensing (CCRS), in Ottawa, and requested that a mission be flown to collect radar imagery of the flood. The mission involved the deployment of the CCRS Convair-580 aircraft which is the platform for their C-band synthetic aperture radar (SAR). The flight took place on April 3rd, 1987.

It is significant to note that the entire mission, including the flight from Ottawa to Fredericton, one hour on the ground in Fredericton, and the return flight, took just 6 hours and 50 minutes. A stop in Fredericton was not essential for a flight of that duration, but was elected in order to deliver the real-time imagery to officials in Fredericton. This long-range flight capability would have been an important factor had the airport at Fredericton been inoperable due to weather conditions.

Imagery was collected for most of the river valley from Perth-Andover to Saint John Harbour in four radar swaths, with the total data acquisition time being ap-

proximately 47 minutes. An aircraft which could respond in such a timely manner could play an invaluable role in flood monitoring, management, and damage assessment alongside traditional methods. The value of a synoptic viewpoint has been pointed out and is underscored in times of disaster, when surface transportation and communication links may be broken.

The overall relief drops some 500 feet between Perth-Andover and Saint John. The radar operators compensated for this difference in terrain elevation on the various passes. The focus of the imagery was quite good in comparison to some of the earlier test images of the Ottawa Valley (Note: the radar was flown for the first time in August, 1986). Water bodies were strongly delineated against cultural features and steep-sided banks. Figure 2.1 shows an example radar scene acquired over the study area. The *bright edge* characteristic of radar imagery was evident on one bank of the river and on the other side it was very difficult to decide whether or not radar shadow was present. This would create a difficulty in delineating flood boundaries if extreme accuracy was required. One method of reducing this problem would be to fly both up river and down river, thus enhancing the return from both river banks in turn.

Areas of open water show up as dark areas in the imagery. A series of jams could be seen starting at Jemseg, near Grand Lake and further downstream at Upper Musquash Island, McAlpines Station, Hampstead, and Kars. Several islands were obviously submerged, with only a single line of trees along the shore to show as a bright edge above the water line (producing a *top-hat* reflector effect). The marshy area between McGowans Corner and Upper Gagetown appears as a very bright region which is unexpected since it is most likely completely flooded. It is felt that this indicates a 'top-hat' reflector effect of trees in flooded forests. This would require corroboration with ground truth data. I think the exciting aspect of this kind of imagery is the speed with which it may be gathered as was indicated by the large amount of information gained from a single 45 minute flight. Areas of current ice jams can be pinpointed and emergency efforts may be more efficiently directed if information is acquired in real or near real time. In fact it would be possible to down-link imagery in real time. If the situation was in an unstable

Figure 2.1: Example Radar Scene

This figure shows the second pass of the CCRS C-band SAR over the study area during peak flooding on April 3rd, 1987.

phase, more flights could be scheduled.

2.2.2 Gagetown Island Study Area

A study area centred on Gagetown Island was chosen primarily because of the intense flood dynamics present around the island. This was identified by visual analysis of the real time imagery. A large ice jam existed at the bend of the river near Lower Jemseg, flooding was evident on both sides of the river and on much of Gagetown Island itself. An interesting flooded forest effect was evident on the island and other flooded areas. And lastly, but importantly, the area was imaged on two successive lines approximately 15 minutes apart and significant ice motion could be observed between lines. Comparison of the map in Figure 1.1 and the image in Figure 2.1 will allow a better appreciation of the place names mentioned above.

Approximately 25 km² of data were chosen from the area surrounding Gagetown Island, New Brunswick, centred at approximately N45°47' latitude and W66°08' longitude. The precise boundaries in the UTM frame fall between 721000 to 726000 metres Easting and 5071000 to 5076000 metres Northing in UTM zone 19. This will translate into a georeferenced image area of 1000 by 1000 pixels at 5 m pixel spacing, which is consistent with the radar resolution in narrow swath mode, the mode used for image acquisition.

At the end of August, 1988, the study area was visited to gain some first hand information and get an idea of what mechanisms might be at work in producing different effects noticed in the radar imagery. The Trans-Canada Highway in New Brunswick follows the Saint John River past the remains of the Perth-Andover bridge, and past the Mactaquac Dam, built in 1968, which is the most important human control over the river's stage at Gagetown.

Closer to Gagetown the relief levels out at Jemseg Flats and it becomes clear how easily the area could become flooded. Meadows stretch off into the distance, outlined by mature trees which tend to follow the river's edge. There is very little relief, but some areas are visibly wet marshlands while slightly higher ground is dry. Past Jemseg River to the east, the banks of the Saint John rise quickly to a

mean elevation of approximately 100 feet. The same is true of the western bank. In between are flat, marshy areas.

Gagetown Island can be described as teardrop shaped with its western side straightened and the narrow end pointing north. The main channel flows around the eastern side of the island and a narrow channel called Gagetown Creek flows directly south on the western side. The following observations of a local resident are included to show that more than weather conditions and river basin topography have an impact on whether flooding will occur in a given area, and on the severity which floods will have when they do occur.

The owner of Gagetown Island, Mr. Moore, grows hay and grains on ridges of the island which he described to be 50 to 200 metres wide. He also lets cattle graze on the island during the summer months and barges them back and forth across Gagetown Creek. Moore held that the Mactaquac Dam caused the 1987 flood and that there was no natural flood at all. There had been some rain, but he believed that the Mactaquac Dam authority had anticipated a huge amount of water coming into its reservoir and dumped twice as much as they needed to so that the water level rose 4-5 feet downstream. Of course the ice broke then and "smashed the hell out of our islands".

That very week, Moore had been hauling hay off the island over 45 cm of ice. When the water level rises, he explained, the whole shape of the channel is changed because of the extremely low relief, so that the river bounces off of Nevers Island and the mainland, coming back to knock the lower east tip of Gagetown Island. Ice piles up at the bend into the south going portion of the river at the Ferry, and backs up into Gagetown Creek. That particular year he lost 30 cords of interval maple that had been cut and stacked in the summer. Each cord, he said, weighs $3\frac{1}{2}$ tons. Moore complained that even under normal conditions, the dam releases too much water without warning and he has lost a dozen boats that way. When the dam releases 3-6 metres of water they will often lose boats that were at dry anchor earlier in the same day. They go over to the island to work and come back to find only the stern in water or the boat actually adrift.

Moore mentioned an 85 year old maple on the eastern shore of the island that

had withstood flooding for 85 years but got completely uprooted in the 1987 flood, the implication being that a natural flood could not have caused this unless it was extraordinarily large. Moore claims that the water temperature is 2-3 degrees higher because of the dam so the river freezes more slowly and now the ice at Gagetown is commonly 45 cm and used to be 60-90 cm. Before the dam was built, they used to be able to drive across. In 1987, the cable of the ferry broke. The ferry operates all winter. It just keeps going back and forth and bulldozers are used to take some of the ice away when it builds up.

In order to understand the high level of backscatter from the trees outlining Gagetown Island, a trip to the island was undertaken. Several features were worth noting. The tall maples were right at the water's edge, in fact hanging over the water. The canopies measured approximately 11 metres (very large trees). There was a steep grade from the tree trunks to the river's edge. Many roots were exposed at the water's edge and there was erosion in between the trees leaving only a line of trees and their roots (corrugated coastline). There were lots of old, mature trees but little or no undergrowth. The height of the bank was approximately 4 metres. In a flood scenario, therefore, the entire bank would have been submerged with only the trees standing above the water, being bashed by the ice.

Back in Fredericton, Brian Burrell at the Water Resource Planning Branch of the Province of New Brunswick, and his colleague Lawrence Peters explained that dams on the river were built in the 1950s and 1960s, and that since the river has to flow through the dams, they have become more conscious of the need for good forecasting. The headponds of the dams have to be controlled in order to alleviate flooding upstream and downstream of the dam.

River stage information is both measured and predicted throughout the river basin. There are 60 weather stations which report daily, starting early in the morning. NOAA satellite data is free to the flood forecasting centre to use in the calculation of snow water equivalents. Forecasting is done using a University of New Brunswick computer. It is a three day forecast providing discharge above Fredericton (at 8 points) and water levels below Fredericton. Readings begin by 7 a.m. and a forecast is available by noon.

When told about Robert Moore and his conviction that the power company was to blame in releasing too much water, Brian Burrell countered by saying that Mactaquac only has about 5-10 percent live storage. The dam is therefore powerless to hold back a major flood.

Chapter 3

Remote Sensing of Ice Jam Floods

In the preceding chapter, the physical nature of ice jam floods as well as the particular circumstances surrounding the 1987 Saint John River flood were described. This chapter considers the advantages and disadvantages of applying remote sensing techniques to the study of this phenomenon.

The great potential of remote sensing for impact assessment and change detection in both the human and physical landscapes has been evident since the first synoptic glimpses of the Earth from aloft. Photographic systems offer images in the full visible region of the spectrum, and also extend into the infrared. Electro-optical sensors partition this energy into particular spectral frequency regions so that data may be recorded or telemetered in a digital format. This format lends itself well to computer analysis. Radar systems operate in the microwave region of the spectrum in which the human eye has no natural sensitivity. Rather than resolving the image with a lens, a radar measures range, intensity and, in the case of synthetic aperture radar, phase information. Some potential applications of remote sensing systems to flood analysis are the following:

- delineation of boundaries of existing floods as well as potential floods (relevant for insurance claims)
- flood forecasting
- planning of urban runoff facilities (storm sewers, etc.)
- assessing river regulatory devices (natural and artificial)

- flood damage assessment

The interpretation of imagery from a given sensor requires a knowledge of the interaction of the electromagnetic radiation used by the sensor and the target in question. The majority of radiation incident on water is either reflected or transmitted. "In visible wavelengths... little light is absorbed, a small amount, usually under 5%, is reflected and the majority is transmitted" (Curran, 1985, p.34). Strong absorption in the near infrared results in a high contrast at land/water boundaries. Most microwave energy is reflected away from the radar due to its strong side-looking orientation. The exception to this is a water feature at right angles to the radar pulse (a wave, for instance).

In considering the use of a given sensor for the monitoring or mapping of a given phenomenon, one must consider the compatibility of multi-temporal data sets, the precision with which the sensor has been calibrated, and the continuity and frequency of data availability. Ramamoorthi et al. (1985) point out that for over a decade, LANDSAT-MSS data has proven itself useful in mapping and monitoring the following characteristics related to flooding:

- the configuration of rivers and changes to the river channel
- flood boundaries
- effectiveness of flood control structures
- changes in flood plain and catchment characteristics

Ramamoorthi et al. (1985) found visual interpretation superior to computer-aided analysis in the case of flood studies. In part, this judgment was attributed to the satellite-based sensor platform which, although it provided a synoptic view of the entire river reach and its drainage pattern, meant that minor streams and drainage patterns could be missed if an automated analysis method was used. Visual interpretive techniques also reduce misclassification of spectrally similar features such as waterlogged areas, flooded fields, and wet soils. Ramamoorthi et al. also point out that a visual superimposition of multi-temporal imagery is much simpler than a

computer aided registration. These are important points to realize when expedience and economics are key issues (as is likely the case in most flood situations).

Kumthekar and Alasingracher (1985), on the other hand, made extensive use of computers in a study of the Shaibi River basin, in India. The study generated a classification of inundated lowlands using topographic maps as a base for supervised classification into the following classes:

- deep water
- shallow water
- wet lands
- lands with some moisture

Ramamoorthi et al. and Kumthekar and Alasingracher clearly have different opinions as to the usefulness of digital analytic techniques. Several factors determine the usefulness of such approaches such as the size of the river catchment (and thus its detectability on the scale of satellite imagery), availability of equipment, and expertise in the operation of that equipment.

A thorough review of the literature concerning the Landsat Multispectral Scanner Subsystem (MSS) to determine its success with respect to flood damage surveys is not intended here, but it is important to point out that such efforts have been made with varying degrees of success. Imhoff et al. (1987) cite the efforts of Berg and Gregoire using Landsat data to map the extent of post monsoon flooding in West Africa. This attempt was limited by “spectral confusion between the water... and obscuring vegetative cover”. They cite the success of Bhavsar in India and Raungsiri et al. in mapping floods in the Mun-Chi river basin in Thailand. All of the attempts to use MSS data, clearly, are limited to data sets collected in the absence of cloud cover. This limitation can seriously curtail operations in monsoon climates where flooding is the result of widespread and long lasting precipitation.

With this background impression of the capabilities of sensors operating in the visible region of the spectrum, and some of the logistical problems associated with

the collection and analysis of their data, the following section will deal with the capabilities of microwave systems, particularly synthetic aperture radar.

3.1 Basic Principles of Radar

Radar, an acronym for radio detection and ranging, is sensitive to energy in the microwave portion of the spectrum (i.e., energy having a wavelength from 1 m to 1 mm). A typical configuration of radar remote sensing systems is side-looking, thus the term *side-looking airborne radars* (SLARs). SLARs send out short pulses of microwave energy perpendicular to the direction of sensor movement and measure the intensity of backscattered energy at a given sampling rate. The time delay between transmission and reception yields the slant range to the target. The motion of the sensor platform causes successive strips of the earth's surface to move through the sensor's field of view, thus building up a two-dimensional image.

The imaging process of a radar is fundamentally different from that of a camera operating in the visible region and, therefore, the information obtained from microwave sensors is different from that obtained from sensors operating in other parts of the spectrum. Radar should be thought of as complementary to other systems rather than as a replacement, and radar imagery should be interpreted with its peculiar imaging process and geometry in mind.

Until the advent of radar, the backbone of remote sensing systems was large format mapping cameras or one of a variety of electro-optical sensors. Most of these optical sensors are passive sensors, relying on the sun or ground target as sources of radiation. Radars provide their own source of radiation in the microwave region of the spectrum and can therefore be operated day and night as well as in overcast conditions due to the decrease in atmospheric attenuation gained by the longer wavelength.

SLARs may be divided into two groups: real aperture systems (commonly termed SLARs) whose spatial resolution is defined in terms of the antenna beamwidth, and synthetic aperture radars (SARs) which utilize signal processing to achieve a much narrower beamwidth in the along track direction than real aperture systems (Ulaby,

Moore, and Fung, 1981, p. 44). The width of the antenna beam determines the spatial resolution in the azimuth direction (along track). The antenna beamwidth of real aperture SLARs is expressed as follows:

$$\beta \simeq \frac{\lambda}{l} \text{ radians}$$

where β is the beamwidth, λ is the wavelength, and l is the horizontal length of the antenna. The azimuth resolution may then be defined as:

$$r_a = \beta R$$

where R is the slant range from the antenna to the pixel. Since the along-track or *azimuth* resolution is defined in terms of the slant range, it will vary across the image (Ulaby, Moore, and Fung, 1981, p. 44). The range resolution is defined as follows: The velocity of light times the pulse duration gives the length of the transmitted pulse and since the pulse must travel both to and from the target, the slant range resolution is simply one half the pulse length. This is converted to a ground range by dividing by $\sin \theta$. Thus, the range resolution is given by:

$$r_r = \frac{c\tau}{2 \sin \theta}$$

where r_r is the range resolution, c is the velocity of light, τ is the pulse duration and θ is the angle from vertical (Ulaby, Moore, and Fung, 1981, p. 44).

For real aperture systems, the way to increase spatial resolution (the limit on how small a feature may be detected by a sensor and yet be distinguishable from its surroundings) in the azimuthal direction is to increase the length of the antenna. This length, however, is limited by the physical and operational constraints of the sensor platform, usually an aircraft. In fact, part of the reason that the radar is side-looking is that the aircraft can only accommodate a long antenna mounted lengthwise along the fuselage (Hovanessian, 1980, p.1).

Synthetic aperture systems use short physical antennas and synthesize very long antennas through signal processing. This results in a very narrow effective beamwidth which, in turn, results in azimuth resolution which is independent of range. The actual azimuthal resolution achieved by the SAR is equal to one half the physical length of the antenna.

One of the major advantages in the use of microwave radiation over visible light is the atmospheric *transparency* of microwaves, allowing their penetration through cloud and, to a certain extent, rain. In addition, radars provide their own source of radiation and, therefore, operate both day and night.

The following characteristics of the radar and terrain affect the intensity of the radar returned signal (Kasischke, 1984, p.2-11):

- wavelength
- polarization
- dielectric constant
- surface roughness
- incidence angle

The wavelength with respect to the size of terrain feature determines whether that feature appears rough or smooth (Hall, 1985, p. 18). A surface that appears rough in the visible wavelengths may appear quite smooth to a C-band radar for instance. Similarly, differences in surface roughness can be expected between C-band and X-band radar imagery since X-band has a shorter wavelength. The CCRS C-band radar has a wavelength of 5.66 cm while its X-band system has a wavelength of 3.24 cm (EMR, 1988, p. 5).

Polarization is important in relation to the orientation of surface irregularities. "Vertically polarized waves will interact with a surface geometry in different ways than horizontally polarized waves, resulting in different radar backscatter between the two. For example, the reflection of horizontally polarized radar waves from ocean waves falls off faster with incidence angle than do vertically polarized waves" (Kasischke, 1984, p. 2-12).

The dielectric constant affects the proportion of incident radiation which is reflected, absorbed, and dissipated. "Water has a high dielectric constant. Thus, moist soils reflect more radar energy than do dry soils, which will absorb the radar wave depending on the dielectric constant of the material" (Kasischke, 1984, p.2-12).

The surface roughness controls the amount of diffuse backscatter while the incidence angle controls the direction of maximum reflection.

The point of relevance, therefore, is that the choice of antenna depression angle, microwave polarization and wavelength will all have an effect on the appearance of the imagery and these factors need to be taken into account in the data acquisition planning process.

3.2 Sources of Geometric and Radiometric Distortion

The geometry of SAR imagery is fundamentally different from that obtained from photographic systems. This difference primarily results from the fact that SAR measures distance rather than angle. The effect this has on the geometry of SAR imagery is discussed below:

3.2.1 Slant Range Scale Distortion

Slant range scale distortion is essentially due to the fact that the distances recorded by the sensor are not planimetric distances between the aircraft and an object, but rather they are slant range distances between the antenna and the object. The scale of a slant range image, therefore, decreases by an amount inversely proportional to the sine of the angle from vertical (incidence angle). If we assume a flat earth, a relatively simple correction may be applied to convert the image to a ground range format.

3.2.2 Topographic Effects

Curran (1985) points out four effects of topography on SLAR imagery:

- corner reflection
- radar shadowing

- terrain layover
- terrain foreshortening

In the imagery of the study area, several instances of the corner reflector effect are evident. In areas of greater local relief, consideration would be given to the other factors listed above. Corner reflection simply involves a double or triple reflection from surfaces at right angles to each other, resulting in a strong return in the direction of the antenna. Radar shadow is caused by any feature which obstructs the path of the oblique radiation and, therefore, prevents its interaction with the surface "hidden" by the feature. Terrain layover occurs when a pulse hits the top of a mountain, for instance, before it reaches the valley. The result is that tall objects lean towards the ground track of the sensor. This is a reversal of the photographic effect of relief displacement. Terrain foreshortening is caused by a pulse hitting a mountain top at approximately the same time as the valley, introducing distortion and ambiguity in the image.

3.2.3 Speckle

Speckle is a grainy pattern which occurs in SAR imagery. It is of interest here because it is the main source of noise in SAR imagery (Ulaby, Moore, and Fung, 1981, p. 583). It arises from the coherent nature of the radar wave, causing random constructive and destructive interference, and hence random bright and dark areas in the image (Kasischke, 1984, p.2-14).

3.2.4 Motion Compensation System

The fact that a synthetic aperture radar image may be built up over several minutes means that any deviation of the aircraft track from a straight line must be detected and accounted for. Aircraft attitude and position data are recorded on a data logging system on board the aircraft known as the MAID system. A Litton-92 inertial navigation system as well as Global Positioning Satellite (GPS) data, and ground-based distance-measuring-equipment (DME) transmitters contribute to provide best

estimates of the aircraft position and attitude at all times. This information is used to steer the SAR antenna to keep it pointing in the direction of zero Doppler and at a constant elevation angle. Phase rotations are also applied to the data to make the image appear as if the aircraft track was a straight line. Any errors which creep into the navigation data could affect the real-time processor imagery.

In some cases, where motion compensation is critical, the real time system may be switched off so that a post flight motion compensation may be performed. This allows use of differential GPS data, or other methods to improve the accuracy of the motion data post-flight.¹

3.2.5 Sensitivity Time Control (STC)

Before data is recorded on high density data tapes (HDDT) the analogue data stream passes through analogue-to-digital (ATOD) converters to be converted into digital pixel values. The dynamic range across the radar swath, however, is too large for the ATOD converters. To compensate for this, a sensitivity time control (STC) function is applied before the ATOD to compress the dynamic range. The STC is optimized for various terrain types. For instance, the CCRS SAR has an ice, water, and land STC. In the case of the Gagetown data set, the imagery was collected using the land STC.

¹Differential GPS refers to the use of a second GPS receiver at a known, stationary location so that any errors in the GPS signal may be removed after the fact.

Table 4.2: Example of LSTSQR.DAT Output

% RS6455 control points used for image registration

{IMAGE COORDINATES}			{SURVEY COORDINATES}		{ RESIDUAL ERROR }		
GCP	LINE	PIXEL	EASTING	NORTHING	EASTING	NORTHING	MAGNITUDE
8	1695	874	721764.19	5071842.00	20.90	0.87	20.92
24	409	1622	718156.25	5076667.00	7.73	-39.62	40.37
25	452	1757	718528.94	5077246.50	12.94	35.34	37.64
27	1515	398	720315.25	5070100.00	-27.45	-0.75	27.46
28	2229	2992	726991.50	5079978.00	2.30	30.46	30.54
29	3295	3538	731784.81	5080762.00	13.79	-14.53	20.03
30	3154	3686	731489.75	5081590.00	10.89	4.84	11.92
31	2113	3335	727071.44	5081526.00	-19.30	-9.31	21.43
32	2155	3397	727319.88	5081729.50	-21.83	-7.30	23.02
=====							
Average					0.00	-0.00	25.93
Standard Deviation					17.96	22.70	9.04

Rotation angle = 20.185 degrees

Squint angle = 0.151 degrees

Line spacing = 3.936 m

Pixel spacing = 4.447 m

/	\	/				\	/	\	/			\
	X			3.694205	1.545420		L			714130.911407		
			=						+			
	Y			-1.358086	4.169800		P			5070498.670363		
\	/	\				/	\	/	\		/	

UTM
coords.

Line &
Pixel

UTM
Offset

Table 4.1 shows the design parameters for RTSP pixel resolution and spacing given by Livingstone et al. (1987). The relatively high resolution data made it feasible to identify the location of ground control points (such as road intersections, etc.) in image coordinates, and translate them into a map grid with quite small errors in position. Once the optimal translation was determined for the control points, it could then be applied to the whole image. The aim was not to develop a perfect model for geometric correction or to compete in any way with commercial geographic information systems (GIS) approaches to this problem, but rather to provide a simple yet effective method of putting several data sources into the same frame of reference. The method used does not really *correct* the geometric distortion present in the image, but rather uses a *rubber sheet* approach to making the image fit the map. The primary objective, after all, was to put the imagery into a frame of reference in which it could be easily compared with other images.

Table 4.1: Design Parameters for RTSP Pixel Resolution and Spacing

Radar Mode	Resolution (m)		Pixel Spacing (m)	
	Range	Azimuth	Range	Azimuth
Nadir	6.0	6.8	4.0	3.89
Narrow Swath	6.0	6.8	4.0	3.89
Wide Swath	18.7	10.9	15.0	6.22

On each radar subscene of the Gagetown Island study area, a set of Ground Control Points (GCPs) were identified and located in the image reference frame, by line and pixel number, using the program **IMG** which I developed for use on a personal computer. It was quite difficult to estimate the line and pixel numbers for some of the GCPs because of the difficulty locating road intersections on the imagery. This was partly due to imperfect motion compensation leading to focus problems in the imagery and partly due to the resolution of the SAR itself. In addition to this, the backscatter from roads is nominally quite low. Estimation of control point location on non-cultural features (e.g., the southernmost tip of an island) proved even more difficult since those features were non-linear in nature. The control points were also identified on a 1:50000 map of the area so that Universal

Transverse Mercator (UTM) coordinates could be measured for each of the image points. Course ground elevation data was available from the map but was not used since the geometric correction would be strictly two-dimensional.

Since a 1 mm measurement error on a 1:50000 scale map translates into a 50 metre error, care was taken to minimize this error. A PDP-11 computer equipped with a digitizing tablet was used to take readings of grid corners (for reference) as well as desired ground control point locations. Ground control points were chosen as close as possible to the river's edge since the transformation model was strictly two-dimensional. After transferring the data back to a PC, the digitizer coordinates were converted into their UTM counterparts.

Not all of the selected GCPs could be identified on any given radar subscene, but a list of line and pixel numbers corresponding to the GCPs that were identifiable was generated for each of the subscenes. The total geometric distortion in any one scene is made up of a number of components. Some of these components are deterministic in nature (i.e., they exist due to certain known characteristics of the imaging process), and there is also a certain amount of residual error after attempting to remove the gross errors.

4.1.1 Deterministic Errors

The model used to translate image coordinates into UTM coordinates includes an offset, a gross rotation, a skewness correction, and a scaling factor in both the line and pixel directions. Using the model, a solution was generated separately for each image. This was done using Choleski's method of Gaussian elimination (Dahlquist, 1969).

Once derived, the transformation was applied to the image coordinates for a set of ground control points so that the average scene distortion could be calculated, and the solution for the ground control points was saved in order to facilitate the conversion of all image pixels.

The derivation of the transformation model assumes an image coordinate system with increasing line number along the x-axis and increasing pixel number along the

y-axis. This corresponds to the image recording configuration on board the Convair-580 and this is shown in Figure 4.1. Throughout the derivation, the notation ' will be used to denote modified parameters. No references are given throughout the derivation since it was accomplished from first principles with the help of the research scientists at CCRS.

Figure 4.1: Image Recording Configuration

Scaling

The scaling component is straightforward and involves only a scalar multiplier for line number and pixel number. The image is scaled independently along these two axes.

$$\begin{pmatrix} L' \\ P' \end{pmatrix} = \begin{pmatrix} l & 0 \\ 0 & p \end{pmatrix} \begin{pmatrix} L \\ P \end{pmatrix}$$

where L = image line number

P = image pixel number

l = line spacing factor (metres)

p = pixel spacing factor (metres)

4.1.2 Skewness

Another distortion evident in airborne radar imagery is a *skewness* or asymmetry of range lines with respect to the zero Doppler direction (normal to the aircraft track).

$$\begin{pmatrix} L'' \\ P'' \end{pmatrix} = \begin{pmatrix} 1 & \sin \alpha \\ 0 & \cos \alpha \end{pmatrix} \begin{pmatrix} L' \\ P' \end{pmatrix}$$

where α is the skewness angle. Ideally, one would have perfectly straight flight paths where data is laid out in strips which are perfectly perpendicular to the aircraft track. In reality, however, targets at the far edge of the radar swath are skewed a positive angle α ahead of the aircraft, such that the far edge is imaged slightly later than the near edge. This is shown in Figure 4.2 below:

Figure 4.2: Image Skewness

4.1.3 Rotation

Most maps are oriented so that the top of the map sheet points in the direction of north. In the UTM system, the abscissa and ordinate axes point to Easting and Northing respectively. The UTM grid is a good two-dimensional approximation of the Earth's surface within the bounds of a particular UTM zone. There are 60 UTM zones to cover the entire globe between latitudes 80° N and 80° S. Each zone is 6° longitude wide with a half degree overlap at the edges (Penguin Dictionary, 1984, p. 565). It is possible to convert coordinates from one zone to another, but position errors would increase with distance from the centre of a given zone.

In order to rotate from image coordinates into the UTM reference frame, a rotation matrix is defined as follows:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \bar{M} \begin{pmatrix} L'' \\ P'' \end{pmatrix}$$

where X = UTM Easting

Y = UTM Northing

$\bar{M}$ = the rotation matrix from the image frame to the UTM frame given below :

$$\begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix}$$

where ϕ is the rotation angle.

Figure 4.3: Rotation from the Image to UTM Reference Frame

The rotation matrix $\bar{M}$ can be derived from Figure 4.3 as follows. P is a point at (r, θ) in the $\begin{pmatrix} X \\ Y \end{pmatrix}$ frame.

$$\begin{aligned} \cos(\phi + \theta) &= \frac{L''}{r} \\ \sin(\phi + \theta) &= \frac{P''}{r} \\ \cos \theta &= \frac{x}{r} \\ \sin \theta &= \frac{y}{r} \end{aligned}$$

$$\text{Now } L'' = r \cos(\phi + \theta)$$

$$\begin{aligned}
&= r(\cos \phi \cos \theta - \sin \phi \sin \theta) \\
&= (r \cos \theta) \cos \phi - (r \sin \theta) \sin \phi \\
&= x \cos \phi - y \sin \phi
\end{aligned}$$

$$\begin{aligned}
\text{and } P'' &= r \sin(\phi + \theta) \\
&= r(\sin \phi \cos \theta + \cos \phi \sin \theta) \\
&= (r \cos \theta) \sin \phi + (r \sin \theta) \cos \phi \\
&= x \sin \phi + y \cos \phi
\end{aligned}$$

Solving for x and y :

$$\text{adding } \left[\begin{array}{l} L'' \cos \phi = x \cos^2 \phi - y \sin \phi \cos \phi \\ P'' \sin \phi = x \sin^2 \phi + y \cos \phi \sin \phi \end{array} \right] \text{ gives } x = L'' \cos \phi + P'' \sin \phi$$

$$\text{subtracting } \left[\begin{array}{l} P'' \cos \phi = x \sin \phi \cos \phi + y \cos^2 \phi \\ L'' \sin \phi = x \cos \phi \sin \phi - y \sin^2 \phi \end{array} \right] \text{ gives } y = -(L'' \sin \phi) + P'' \cos \phi$$

Therefore,

$$\vec{M} = \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix}$$

4.1.4 Offset

An X and Y offset is applied in order to bring the relatively low valued image coordinates into the range of a given UTM zone. In the northern hemisphere, the origin for a UTM zone is the equator and a point 500 km west of the central meridian for that zone.

$$\begin{pmatrix} X' \\ Y' \end{pmatrix} = \begin{pmatrix} X \\ Y \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix}$$

where (X_0, Y_0) is the UTM offset
 (X', Y') is the translated UTM position

4.1.5 Overall Model

Combining scaling, skewness, rotation, and offset together we get the overall transformation from image line and pixel numbers to UTM positions:

$$\begin{pmatrix} X' \\ Y' \end{pmatrix} = \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} 1 & \sin \alpha \\ 0 & \cos \alpha \end{pmatrix} \begin{pmatrix} l & 0 \\ 0 & p \end{pmatrix} \begin{pmatrix} L \\ P \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix}$$

Simplifying yields:

$$\begin{pmatrix} X' \\ Y' \end{pmatrix} = \begin{pmatrix} l \cos \phi & p \sin(\alpha + \phi) \\ -l \sin \phi & p \cos(\alpha + \phi) \end{pmatrix} \begin{pmatrix} L \\ P \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix}$$

Now if we let

$$\begin{aligned} A &= l \cos \phi \\ B &= p \sin(\alpha + \phi) \\ C &= -l \sin \phi \\ D &= p \cos(\alpha + \phi) \end{aligned}$$

then

$$\begin{aligned} \phi &= \tan^{-1}\left(\frac{-C}{A}\right) \\ \alpha &= \tan^{-1}\left(\frac{B}{D}\right) - \phi \\ l &= \sqrt{(A^2 + C^2)} \\ p &= \sqrt{(B^2 + D^2)} \end{aligned}$$

4.2 Geometric Correction Software

A routine called LSTSQR was developed with the aid of Jack Gibson (CCRS), which solves the system of linear equations relating image line and pixel numbers to a UTM base. The software requires as input a list of line and pixel numbers measured at ground control points on the radar image and the corresponding UTM positions (either surveyed or measured from a topographic map). The input format should be an ASCII file with the following format:

```
%RS4876 22-AUG-86 C-BAND HH-POL 86-234-18:12:36
2 1248 3804 422725.79 5014858.02 124.40
```

```

4 1712 2994 425780.07 5017543.08 99.15
5 2319 3362 427795.86 5015235.64 100.22

```

The first line of the file should be a comment line which describes the image. Subsequent lines contain the following parameters listed as they occur in the file from left to right:

- ground control point number (identifier)
- image line number
- image pixel number
- UTM Easting
- UTM Northing
- elevation (m)

Here, elevation is included in the file for completeness but is not used in the calculations. The user must also supply the total number of lines in the image when prompted by the routine. The computed displacements between measured and surveyed ground control points are calculated as well as the rotation angle, skewness angle, and line and pixel spacings corresponding to the transformation model. The results are written to a file called 'LSTSQR.DAT' (an example of which is depicted in Table 4.2).

4.3 Results for Gagetown Imagery

A summary of the results for the images of the Gagetown study area is presented in Table 4.3. The results indicate that the skewness is generally less than 3 degrees, and that the average geometric distortion in a scene is less than 4 pixel diameters. For the best case examined, the average displacement was 2 pixel diameters. It must be kept in mind that the effect of terrain relief has not been taken into consideration here so that these results may not be as good as they could have been if relief had

Table 4.2: Example of LSTSQR.DAT Output

% RS6455 control points used for image registration

{IMAGE COORDINATES}			{SURVEY COORDINATES}		{ RESIDUAL ERROR }		
GCP	LINE	PIXEL	EASTING	NORTHING	EASTING	NORTHING	MAGNITUDE
8	1695	874	721764.19	5071842.00	20.90	0.87	20.92
24	409	1622	718156.25	5076667.00	7.73	-39.62	40.37
25	452	1757	718528.94	5077246.50	12.94	35.34	37.64
27	1515	398	720315.25	5070100.00	-27.45	-0.75	27.46
28	2229	2992	726991.50	5079978.00	2.30	30.46	30.54
29	3295	3538	731784.81	5080762.00	13.79	-14.53	20.03
30	3154	3686	731489.75	5081590.00	10.89	4.84	11.92
31	2113	3335	727071.44	5081526.00	-19.30	-9.31	21.43
32	2155	3397	727319.88	5081729.50	-21.83	-7.30	23.02
=====							
Average					0.00	-0.00	25.93
Standard Deviation					17.96	22.70	9.04

Rotation angle = 20.185 degrees

Squint angle = 0.151 degrees

Line spacing = 3.936 m

Pixel spacing = 4.447 m

/ \	/			/ \	/	/		/ \
X		3.694205	1.545420	L		714130.911407		
	=				+			
Y		-1.358086	4.169800	P		5070498.670363		
\ /	\			/ \	/	\	/	

UTM
coords.

Line &
Pixel

UTM
Offset

Table 4.3: Gross Geometric Distortions in the Real-Time Data

Scene	Rotation (deg)	Skewness (deg)	Spacing		Offset		Error (m)
			line (m)	pixel (m)	X (m)	Y (m)	
CCRS-1	19.05	2.31	3.84	4.46	718047.98	5070915.17	10.61 +/- 5.34
CCRS-2	81.26	1.04	4.03	4.38	719612.11	5078077.01	18.81 +/- 8.11
MDA-1	18.15	2.49	5.50	4.22	726692.46	5076457.73	11.58 +/- 7.82
MDA-2	17.27	-1.08	5.52	4.27	718640.34	5072807.21	15.69 +/- 10.46
MDA-3	18.48	1.23	16.61	15.73	716287.37	5071264.31	16.91 +/- 8.68

been considered. The statistics presented for the wide swath image (MDA-3) are less reliable than the other images since measurement accuracy of the ground control points from the imagery is reduced in wide swath mode.

4.4 Image Resampling

Once the transformation matrix (image coordinates to geocoded UTM coordinates) was determined for each image, it was necessary to resample the image to a 5 m grid. What was required, therefore, was the inverse transformation (from UTM to image coordinates) so that particular UTM coordinates corresponding to the study area and desired pixel spacing could be given and appropriate line and pixel numbers computed. It had been established that UTM x and y coordinates could be computed from line and pixel numbers by multiplying by the appropriate transformation matrix as follows:

$$\begin{pmatrix} X' \\ Y' \end{pmatrix} = \bar{M} \begin{pmatrix} L \\ P \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix}$$

If we want to solve for line and pixel number, we can do the following:

$$\bar{M} \begin{pmatrix} L \\ P \end{pmatrix} = \begin{pmatrix} X' \\ Y' \end{pmatrix} - \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix}$$

And,

$$\begin{pmatrix} L \\ P \end{pmatrix} = \bar{M}^{-1} \left[\begin{pmatrix} X' \\ Y' \end{pmatrix} - \begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} \right]$$

Therefore, we need to find $\bar{M}^{-1}$. Once the resampling process was carried out for each image, the data from different sources could be more readily compared. The exercise of deriving the systematic corrections necessary proved very useful to the author's understanding of the georeferencing process.

Chapter 5

Radiometric Processing

The image contrast was quite acceptable for the CCRS data before any radiometric processing, but some enhancement was required for the MDA X-band data. The X-band data had a small dynamic range, revealed by its histogram. MDA confirmed that the data was collected at a low gain setting in order to avoid bright target saturation. A contrast stretch was applied to the data in order to attain some degree of uniformity between X and C-band data. The distribution of the intermediate grey tones is still, of course, dictated by the histogram for each separate image. No attempt was made to balance the two scenes radiometrically beyond this rudimentary contrast stretch.

The contrast stretch was accomplished using Atlantis Scientific's SAR workstation software for PCs called SARDM1. This package was developed specifically for CCRS. A 256-level histogram was generated for each image as shown in Figure 5.1 and the tails of the histogram were clipped at the edges of the main lobe of the distribution. In this way, the dynamic range was actually compressed to the digital limits of the main lobe of the histogram. Following this, the minimum image value was subtracted from each pixel and then each pixel was scaled by the resultant maximum image value. This left the image in a floating point representation with values between 0.0 and 1.0. These were then multiplied by 255 and converted back to byte format. The result was contrast-stretched imagery which spanned the full 8-bit dynamic range.

Figure 5.1: Image Histogram Computed by SARDM1

The top portion of this figure displays the second C-band image after it was contrast stretched using Atlantis Scientific's SAR workstation software (SARDM1). A 256-level histogram is shown below. SARDM1 allowed the tails of the original distribution to be clipped at the edges of the main lobe.

5.1 Filtering

One advantage to digital image analysis is the ease with which the imagery may be manipulated such that geographic features of interest are enhanced. There are many different methods of image enhancement which either emphasize or de-emphasize abrupt changes in brightness values of adjacent pixels. Low-pass filters smooth out the differences between neighbouring pixels. High-pass filters, on the other hand, emphasize the same differences.

Decreasing the noise in an image or reducing the speckle effect in radar imagery with a low-pass filter can help to make boundaries of nominally homogeneous areas stand out more clearly. On the other hand, high-pass filters can enhance natural edges in the imagery which may go just as far in making the boundaries of regions stand out. SARDM1 includes a Lee-filter, named after Jong-Sen Lee, which is an adaptive speckle filtering algorithm. The algorithm uses local statistical measurements of mean and variance over a window to yield a filtered image which has reduced speckle and yet retains good edge detail. SARDM1 also offers a FIR (finite impulse response) filter implementation using user-supplied filter matrices. This allows the definition of many other kinds of filters, including high-pass, low-pass, and edge enhancement filters.

One such edge enhancement uses the Sobel operator (Ballard and Brown, 1982, p. 77) which can help to enhance vertical or horizontal edges in the imagery or both. The Sobel operator was applied using the FIR function of SARDM1 and is really a set of two matrices which are applied to the original image separately and their effects combined later. The two matrices are:

$$\begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix} \text{ and } \begin{pmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{pmatrix}$$

They emphasize vertical and horizontal edges, respectively. Once calculated, the two filtered images may be recombined by first squaring the individual images, adding the two components, and then taking the square root. This yields a high contrast image which is more useful for analysis than the original image which requires more

involved feature delineation.

Figure 5.2 shows the effect of a 7 x 7 Lee-filter (speckle reduction filter) and the Sobel edge operator on the same original image. The original image is presented in Figure 2.1. Notice the greater degree of homogeneity evident in the Lee filtered image. The fragments of ice which form the ice jam have a very detailed texture which is enhanced by the Sobel operator. The Lee filter, on the other hand, has a smoothing effect which renders the entire ice jam a more uniform brightness. This would aid in an automated classification.

Figure 5.2: Lee-Filter and Sobel Edge Filter Comparison

The top portion of this figure displays the second C-band image with a 7 x 7 Lee-filter (speckle reduction filter) applied. The smoothing nature of this filter gives a greater degree of local homogeneity in contrast to the edge enhancing Sobel operator, the results of which are seen in the lower image. In the Sobel filtered image, the detail in the fragments of ice forming the ice jam has been enhanced.

Chapter 6

Comparison of Data Sets

In a purely visual comparison, the human brain is able to compare images even when the viewing geometries for the images are quite different. One imagines slant range data to be stretched into ground range format or one mentally rotates an image into a more familiar orientation. Even greatly distorted features may be recognized by examining them in the context of known features. This kind of visual geometric correction is done intuitively. Although it would be simpler to compare two rectified and registered images, the mind is not hampered much by this deficiency, although some people are better at it than others.

Today's personal computers are offering alternatives to this *visual computing*. The past several years have seen the emergence of high-end graphics subsystems on personal computers and faster generations of processors. Images may be scanned with hand-held and table-top scanners and then manipulated in digital format. In such a way, imagery is made more directly interpretable by the analyst, who may still perform a visual analysis of the partially processed data.

Computer analysis usually imposes certain restraints on data format and representation. The data must be in a form readable by a given piece of software and must exist in a known, pre-described format to be reliably interpreted. This is not to say that a digital analysis would not be capable of compensating in ways analogous to the visual method, given a sufficiently sophisticated algorithm. A great stumbling block to the digital approach, however, is locating geographically equivalent points in each image. The low-level image matching and shape recognition functions of the

human vision system are taken for granted in everyday use, but pose a significant problem to computer image matching algorithms. Great lengths are taken to register the images to be compared so that the common reference points are set up in advance.

This chapter explores the merit in both the visual and computer-aided approaches with respect to several different types of image comparisons made possible through the data sets available.

6.1 Ice Jam Dynamics

Part of the reason for the choice of study area was the ice jam dynamics at the time the imagery was taken. The two passes of the CCRS radar which imaged this section were approximately 20 minutes apart and significant ice motion may be noted between the two passes. Pass 3 occurred at approximately 16:45 while pass 4 was 20 minutes later at 17:05.

Figure 6.1 shows the two passes with the earlier pass at the top and the later pass at the bottom. Close observation in the river channel where the ice was jamming reveals that several of the ice floes apparent in one image appear again in the next image slightly farther downstream (towards the bottom of the image). As well, a large fracture in the ice may be seen in the image at the top of the page which has completely closed in by the time of the next pass, illustrated by the image at the bottom of the page. Since the images have both been resampled to the UTM grid, it is possible to measure the line and pixel numbers for identifiable floes in both images and compute the distance travelled by each floe.

I chose two prominent floes, which have been identified by numbers one and two on the two images, and measured the line and pixel numbers for a given point on each floe. Knowing the pixel spacing for the registered images, the average distance each floe moved was calculated to be 674 metres over approximately 20 minutes. This is equivalent to 0.56 m/s. So the ice was accumulating at this bend in the river but was still in motion, albeit quite slowly. The destructive ice jam that took the Perth-Andover railway bridge down with it early on the morning of April 2nd, was

Figure 6.1: Ice Jam Dynamics

This figure shows the two C-band SAR images with the earlier pass at the top and the later pass at the bottom. Land areas have been masked from both images so that only the river is visible. Points marked 1 and 2 indicate large floes which have moved during the 20 minutes between passes. As well, a large fracture in the ice may be seen in the image at the top of the page which has completely closed in the second image.

Floe	Pass 3 line #	Pass 3 pixel #	Pass 4 line #	Pass 4 pixel #
1	149	664	273	688
2	424	702	565	676

Table 6.1: Floe positions between passes

stationary before it broke. This meant that the water welling up behind it built up an enormous amount of pressure.

The ice flowing around Gagetown Island also had a destructive impact, since the channel took on a changed shape due to the high flood waters and low relief. This was indicated by Robert Moore's comments, in Chapter 2 concerning damage to trees on his island.

In considering how best to differentiate ice from water in the river channel, it was deemed useful to try to isolate the river from its background. This was done by first digitizing the *normal* river boundaries as they were demarcated on a 1:50000 topographic map. Points between the digitized points were interpolated to 3 m so that there would be no gaps in the 5 m resolution raster display. The next step was to fill the land areas with one pixel value so that when a bitwise OR was performed with another image, the land areas would have an opaque quality to them because of the minimum digital value of 100.¹

Conversely, a second raster image with only the river areas filled was produced so that when a bitwise AND was performed with another image, only the river would be visible (land would appear as black). This proved to be a very useful image pair to have for the analysis since isolating the river and land areas makes classification based on intensity level more reliable.

The problem of displaying change between two images took some thought. The idea of displaying each image in a different colour seemed obvious enough but the ice itself had a relatively low image intensity. This meant that the underlying features

¹The OR operator produces a 1 in the corresponding output bit position if *either* of the input bits in that position is 1. The AND operator produces a 1 in the corresponding output bit position if *both* of the input bits in that position are 1.

did not *show through* the first image. Bitwise ANDs were performed on the two scenes with the river mask so that the scenes could basically be divided into two classes: ice and water. The water had a low intensity while the ice had a higher overall intensity. The intensities were scaled by a factor of two and the two scenes were displayed using blue and green. Red was used to display a map grid with grid lines every kilometre.

With the combination of the two images viewed as in Figure 6.2, changes between the two images may clearly be seen. Ice that appears as pure green existed only in Pass 3, while ice that appears blue existed only in Pass 4. Light blue colours represent a mixture. Features in the ice may be tracked between images while some features (such as the long blue rift) do not appear in both, indicating that the rift filled in. The change in position of the ice edge between passes is also clearly visible.

6.2 Flooded vs. Non-flooded Imagery

In the case of the Gagetown study area, it so happened that the imagery taken during the flood was at C-band and the imagery two months before the flood was taken with a different radar at X-band. So the flooded vs. non-flooded comparison happened concurrently with the X-band vs. C-band comparison. As well, of three different passes over the study area, only one of the X-band images offered complete coverage and this was the wide swath mode image. The STAR-2 X-band radar data has a slant range resolution of 18 metres. The resampling process has, therefore, somewhat oversampled the original image.

Several differences are immediately apparent in Figure 6.3 ² Firstly, in the X-band image the river is frozen over so there are no areas of water visible. Secondly, there are large portions of Gagetown island and other low lying areas that are visible in the X-band imagery. These same areas are covered by flood water in the C-band imagery. The patterns of highlights and shadows on the two images are different due to the different flight paths. Detail in the treed areas on Gagetown Island is

²Here the image reproduction quality on paper makes these differences less obvious than when viewed on the computer monitor.

Figure 6.2: Ice Jam Change Detection

With the combination of the two C-band images using green for Pass 3 and blue for Pass 4, changes between the two images may clearly be seen. Ice that appears as pure green existed only in Pass 3, while ice that appears blue existed only in Pass 4. Light blue colours represent a mixture. Features in the ice may be tracked between images while some features (such as the long blue rift) do not appear in both, indicating that the rift filled in. The change in position of the ice edge between passes is also clearly visible.

Figure 6.3: X-band and C-band Comparison

This figure shows a C-band image during the flood and an X-band image taken two months prior to the flood. Note the large areas of Gagetown island and other low lying areas that are visible in the X-band image, but appear as dark water-covered areas in the C-band image. The Scovil ferry is distinctly visible at the bottom of the X-band image with the cable that guides the ferry appearing as a thin bright line.

lost on the X-band because of the reduced resolution. The Scovil ferry is distinctly visible in the X-band image at the bottom of the image with the cable that guides the ferry clearly visible as a thin bright line. This is not apparent at all on the C-band image. It was felt that it would not be advantageous to combine these two images digitally in any way.

6.3 Cultural Feature Masking

After digitizing the land/water boundaries from a topographic map and converting these data to a raster format in the same reference frame as the imagery, I had supposed that estimates might be made of the flooded area, or that such data could provide the basis for warnings regarding the flooding of significant cultural features such as highways.

Unfortunately, classification of flooded area proved to be problematic since other features in the imagery, such as fields, have intensity values as low as the water. With the masking of land so that all that is seen is the river, the differentiation between water and ice becomes much simpler. Perhaps following the intensity gradient from the river on to the land, one might be able to estimate flooded area but such a procedure would be problematic where there are trees near the shoreline as is the case on Gagetown Island.

Visual analysis would not be limited by such technical problems, however, and therefore a method was still sought whereby cultural information could be overlaid on the imagery. Part of a New Brunswick flood risk map was scanned into a grey scale TIF (Tagged Image Format) file. It was converted to the same image file format as the imagery and resampled in the same fashion to conform to the study area. The map was then *added* to an image by first scaling the image and map by 0.5 and then performing a pixel by pixel addition. Figure 6.4 shows the combination of map and image.

The mottled tones on the scanned map indicate the approximate boundary of the 1973 flood at its highest point.³ This gives an indication of those areas at

³The map was scanned from a 1:500000 flood risk map produced by the New Brunswick Depart-

Figure 6.4: Cultural Feature Masking

The image presented here is a combination of a scanned flood risk map with a SAR image. The map was added to the image by first scaling the image and map by 0.5 and then performing a pixel by pixel addition. The mottled tones on the scanned map indicate the approximate boundary of the 1973 flood at its highest point. The map was scanned from a 1:50000 flood risk map produced by the New Brunswick Department of the Environment, Water Resources Branch, in April, 1981. This gives an indication of those areas at risk of flooding.

risk of flooding. As well, some roads are evident in the scanned map and the road network is fairly closely registered with the image. This form of image combination is analogous to looking at the map and image superimposed on a light table.

6.4 Airphotos vs. Radar Imagery

Figure 6.5 shows a resampled scanned aerial photo below a C-band radar image. The aerial photo was acquired by Energy Mines and Resources in June, 1979 and has a scale of approximately 1:50000. Here we have the comparison between a sensor operating in the visible region of the spectrum and one operating in the microwave region. One can see quite vividly that radar cannot be viewed as a straight substitute for aerial cameras but should be viewed as a complementary sensor. The detail available in the aerial photograph of this area is much greater than in the radar image. This particular aerial photo was scanned with 16 possible grey levels. A more sophisticated scanner could have scanned this with 256 levels yielding more tonal depth (which was present in the original photo).

The photograph shows a summer-time view of the study area with the river pictured in its non-flooded state. Prior to the ability to render photographic images in a rasterized digital format, a manual effort would have to be made to project a transparency of the photo on to a known base using an optical projector. This would allow, for instance, the transcription of a particular land/river boundary from the photo to the map.

The advantage of the rasterized and registered version is convenient combination with other forms of imagery, and digital analysis of the airphoto itself. One problem evident in the airphoto in Figure 6.5 is the sun glint on the water near the lower tip of Gagetown Island. This would pose some difficulty in a classification performed on the airphoto.

Figure 6.5: Airphotos vs. Radar Imagery

This figure shows a resampled aerial photo below a C-band radar image. The aerial photo was acquired by Energy Mines and Resources in June, 1979 and has a scale of approximately 1:50000. This offers a comparison between a sensor operating in the visible region of the spectrum and one operating in the microwave region. The photograph shows a summer-time view of the study area with the river pictured in its non-flooded state. Notice the sun glint in the airphoto near the lower tip of Gagetown Island.

6.5 Detection of Ice Jams and Flooding

If the classification of an image was constrained to look at only those areas within known geographic boundaries (i.e., the river's normal boundary), the automation of ice jam detection would be more feasible. This was accomplished and described in the section on ice jam dynamics. There, map data were used to mask out either the river or land portions of the image so that classification might be isolated to either region.

Filters, discussed in the preceding chapter could, for instance, further aid in isolating ice from water by reducing local variations in the intensities measured in ice and water regions. Further steps could be taken to calibrate the radar data radiometrically so that multiple data sets could be compared easily.

It may seem unrealistic to suppose that one could perform the same processes of map digitization and control point location, registration, resampling, etc. that were carried out for this small experimental study area, while monitoring large areas for ice jams. With faster and faster computers, however, this is becoming possible. In the case of the Saint John River valley, the ice breakup will routinely occur within a short period of the year. Ice jam monitoring, therefore, would be confined to this very short time period and could even be concentrated in those portions of the river most susceptible to ice jam formation. With the advent of tools like the Global Positioning Satellite (GPS) system which gives 3-dimensional coordinates of aircraft position in real time to within 100 metres, it becomes possible to compute fairly precisely the area being imaged without a need to register to a map. In fact, through the use of differential GPS, a second stationary GPS receiver is used to reduce errors in the moving receiver to just a few metres.

Other methods might be employed to eliminate the manual control point matching. Unique terrain features such as the patterns formed by trees half way down Gagetown Island could be modelled and the expected image subscene simulated for given flight parameters (look direction, altitude, etc). A correlation operation could then be performed to *find* the subscene in the real radar image. Unique clear-cut patterns around CFB Gagetown would also be candidates for such an approach. Each

target located would improve the overall registration for the entire scene. These operations would be demanding computationally, but with faster and faster computer hardware this will pose less of a problem (McCann and Barr, 1986).

Several satellite-borne radars will soon be launched or are already in orbit. The European (ERS-1) satellite, the Canadian (Radarsat) and the Japanese (JERS-1) satellites will allow key areas to be routinely monitored without the need for special purpose aircraft sorties. The repeat satellite coverage, however, might not be adequate due to the short life-span for ice jams, necessitating airborne coverage.


```

/* Change filename to uppercase */
strcpy(infile,strupr(argv[1]));

/* get name of ground control point file */
fp = fopen(infile,"r");
if (fp==NULL) {printf("Error opening %s\n",infile); exit(1);}
fpout = fopen("matrix.dat","w");
if (fpout==NULL) {printf("Error opening MATRIX.DAT\n"); exit(1);}

/* find out how many control points need to be read in */
fgets(comment,70,fp);
printf("%s",comment);
printf("{ IMAGE COORDINATES } { MAP COORDINATES }\n");
printf(" GCP LINE PIXEL EASTING NORTHING ALT\n");
ngcp=0;
while (!feof(fp)) {
    fgets(line,70,fp);
    if (!feof(fp)) {
        printf("%s",line);
        ngcp++;
    }
}
printf("# of ground control points=%d\n",ngcp);
rewind(fp);
fgets(comment,70,fp);

/* allocate memory for matrices */
ap=dmatrix(1,3,1,3); /* A transpose times A */
bp=dmatrix(1,3,1,2); /* A transpose times B */
b=dmatrix(1,ngcp,1,2); /* UTM positions (transformed) */
img=dmatrix(1,ngcp,1,3); /* Image line,pixel numbers */
code=dmatrix(1,ngcp,1,1); /* GCP identifiers */
imgcpy=dmatrix(1,ngcp,1,3); /* Copy of IMG */
utm=dmatrix(1,ngcp,1,3); /* UTM positions (measured from map) */
x=dmatrix(1,3,1,2); /* Transformation matrix */
r=dmatrix(1,ngcp,1,2); /* displacement error (easting,northing) */

/* initialize image coordinate matrices and utm position matrices */
for (i=1;i<=ngcp;i++) {
    fgets(line,70,fp);
    sscanf(line,"%lf %lf %lf %lf %lf %lf",&code[i][1],&img[i][1],&img[i][2],
        &utm[i][1],&utm[i][2],&utm[i][3]);
    img[i][3]=1.0;
}

/* make a copy of the image line and pixel numbers */
matcpy(img, 1, ngcp, 1, 3, imgcpy);

/* multiply image coordinate matrix by its own transpose */
matatb(img,1,ngcp,1,3,imgcpy,1,ngcp,1,3,ap);

```

which would lower the albedo of the ice and hence speed up the melting process (Hall and Martinec, 1985, p. 101).

The resolution of the radar has been shown to be adequate to yield information for these purposes. The recurring nature of the problem of ice jams in New Brunswick means that the techniques derived here could be expanded on and applied routinely during the annual ice break-up period. Canada has many other rivers which may pose similar threats to populated areas. The same technique could be applied to the study of those rivers as well.

The algorithms derived for the correction of gross geometric errors as well as the filtering techniques could be applied to SAR data of other targets, be they agricultural, urban, etc. and could also be applied to data from other sensors. I have already demonstrated that these techniques work for aerial photographs, map data, and SAR imagery.

The extent to which this kind of analysis could be automated would depend on several factors already mentioned such as:

- the existence of accurate digital map data to delineate river boundaries.
- the degree to which the geocoding of SAR data may take place using sensor platform position and attitude data, or utilizing distinctive features in the imagery that might be matched with existing models of those features, and hence matched with their geographic coordinates.
- the size of the geographic area of interest.
- the resolution desired.
- the computing platform and, hence, overall processing speed.

There is no reason why such a level of automation could not be achieved, especially since the area to be analyzed would be well known and would not change significantly from year to year.

CCRS is now developing an interferometric SAR (INSAR) where a second receiving antenna is mounted on one side of the fuselage and the path difference between

the two returns is recovered from the phase information in the signal. The path difference can be used to estimate the elevation at each pixel across the swath and ultimately yield a digital elevation model in the same frame of reference as the slant range image. This information can in turn be used to correct for terrain-induced distortions. This technique would be useful for areas where the river lies in a deep valley, where it would be difficult to find control points to perform satisfactory geometric correction.

7.1 Approaches to Image Interpretation

A particular method of digital analysis using a personal computer has been pursued while imagining the steps that would have been taken for a manual visual analysis. If one desired only to get an overview of the situation for the entire Saint John River, with the aim of deciding where to concentrate emergency efforts or evacuation procedures, then I see no point in proceeding beyond the initial rendering of the processed SAR data into visual grey tones (i.e., the real-time silver paper product produced on board the Convair-580). This is the product which was handed to officials from the Flood Forecasting Centre within about an hour of the Convair reaching New Brunswick. It is also the imagery I used to choose my study area.

Furthermore, a visual inspection of the real time data can provide estimates of flooded extent despite the geometric problems the imagery might have and the fact that the normal river boundary would be obscured by water. If a more quantitative analysis of a particular area is required, then a digital format is optimal. If an automated system is the goal, then an investment in software is justified; but some thought should be given to what the requirements are before a methodology is devised, since the possibilities alluded to for digital analysis are endless and should be restricted to what is necessary.

Nevertheless, change detection and the long term monitoring of change can lead to a more complete understanding of the system being observed, if only through building up the number of independent observations. I would, therefore, challenge geographers to embrace and explore the technology which allows change to be de-

tected. Geographic information systems (GIS) can be used as a way of combining layers of geographic data much in the way a light table would be used to combine layers of information stored on transparent film. Remote sensing and computers should be seen as tools with which to uncover the information and to complement the existing tools of manual, visual image interpretation which preceded them.

Whether a strictly visual or computer-aided approach is used, both methods are largely complementary and are not as disjoint as one might think. In a manual method, one might still find ways to correct the geometry of the imagery or, for instance, put it in a more directly useful frame of reference through the aid of an optical projector. We need to be aware of the continuum of approaches possible and use the tools most appropriate to the task at hand. Digital data does not, therefore, implicitly require a fully digital analysis. Even the real time imagery on the plane is derived from a digital data stream but the data are not necessarily used by the analyst in a digital form.

Having said that, I believe that the current trend is towards digital analysis and computer automation rather than more conventional techniques in the area of flood monitoring, as well as other change detection efforts. New earth observation satellites are being launched and more and more processes are being automated to the point where raw remotely sensed data are almost unacceptable as a commercial product. We expect a certain degree of sophistication in our remotely sensed image products. But I think we sometimes lose sight of the problems we are trying to solve when we become wrapped up in algorithm deficiencies and prediction errors instead of finding constructive ways to really use the information. My point is simply that no matter how technologically supported our monitoring information is, we have really come no closer to managing the hazard of flooding unless we use the information to try to reduce or eliminate the damages caused by flooding. To that end, I hope that the methods described in this paper can aid in the establishment of flood risk zones, the settlement of post-flood damage claims, and in the provision of a synoptic viewpoint from which to gain a better understanding of ice jam flooding processes.

Appendix A

Summary of Software

The following programs were developed by me as tools to aid in the data analysis portion of my research.

- BYTELOAD** Loads a subsection of a UNIDSK (CCRS imagery format) file into MATLAB (scientific and engineering numeric computation program)
- GRID** Produces an image file containing a UTM grid (1 km spacing)
- IMG** Display program for SARDM1 files.
- IMGADD** Adds two images on a pixel by pixel basis by first dividing by 2 to retain 8 bit dynamic range.
- IMGAND** Performs a bitwise AND on two images on a pixel by pixel basis.
- IMGOR** Performs a bitwise OR on two images on a pixel by pixel basis.
- LSTSQR** Translates image coordinates into UTM coordinates including an offset, a gross rotation, a skewness correction, and a scaling factor in both the line and pixel directions. This was done using Choleski's method of Gaussian elimination.
- MAPFILL** Fills either land or water areas from the digitized land/water boundary.
- MDADUMP** Dumps a CCT produced by MDA to a UNIDSK file.
- RESAMP** Resamples the image data into UTM frame using results from LSTSQR.
- RGBDISP** Display program for SARDM1 files (red, green, and blue components in separate files)
- TIFFCNV** Converts TIFF files (scanned maps) to SARDM1 format
- UNIDM1** Converts a UNIDSK file (CCRS imagery format) to a SARDM1 (Atlantis Scientific) format file

Appendix B

Geometric Correction Software

The following listings contain the C code for programs LSTSQR and RESAMP described in the previous section. The LSTSQR program was compiled using Microsoft QuickC 2.0. Output generated by the LSTSQR program is used later by RESAMP, which was compiled using Metaware High C in order to take advantage of the extended memory available on my 386 PC. These programs were written by me using certain utility routines published in *Numerical Recipes in C: The Art of Scientific Computing*, William H. Press, New York: 1988, Cambridge University Press. The utility routines allocate and deallocate memory for vectors and matrices in keeping with the algorithm implementations throughout the book. The routines were therefore adopted in my software in order that the Gaussian elimination method might be used. In keeping with copyright restrictions, I have not reproduced those sections of code here.

```
/******  
GAUSSJ.H  
*****/  
  
#include <malloc.h>  
#include <stdio.h>  
#include <math.h>  
  
/* macros */  
#define r2deg 57.29577951 /* radians to degrees conversion factor */  
#define MAX(a, b) (((a) > (b)) ? (a) : (b))  
#define MIN(a, b) (((a) < (b)) ? (a) : (b))  
#define SQR(x) ((double)(x))*((double)(x))  
#define SWAP(a,b) {double temp=(a);(a)=(b);(b)=temp;}  
  
/* function prototypes of Numerical Recipes routines */  
/* ----- */  
  
/* standard error reporting function */  
void nrerror(char error_text[]);  
  
/* allocate and de-allocate memory for an integer vector */  
int *ivector(int nl, int nh);  
void free_ivector(int *v, int nl, int nh);  
  
/* allocate and de-allocate memory for double precision matrices */  
double **dmatrix(int nrl, int nrh, int ncl, int nch);
```

```

void free_dmatrix(double **m, int nrl, int nrh, int ncl, int nch);

/* gaussian elimination routine */
void gaussj(double **a, int n, double **b, int m);

/* function prototypes of my own routines */
/* ----- */

/* matrix multiply */
void matmul(double **a, int arl, int arh, int acl, int ach,
            double **b, int brl, int brh, int bcl, int bch, double **c);

/* matrix A times transpose of matrix B */
void matatb(double **a, int arl, int arh, int acl, int ach,
            double **b, int brl, int brh, int bcl, int bch, double **c);

/* duplicate a matrix */
void matcpy(double **a, int arl, int arh, int acl, int ach, double **b);

/* subtract two matrices */
void matsub(double **a, int arl, int arh, int acl, int ach,
            double **b, double **c);

/*****
LSTSQR.C
*****/

#include <string.h>
#include "gaussj.h"

int main(argc,argv)

char *argv[];                /* command line arguments */
int argc;                    /* number of command line args */

{
    double **ap,**bp,**b,**rz,**imgcpy,**utm,**x,**r,**code;
    double totx,toty,totr,totx2,toty2,totr2,read;
    double avx,avy,avr,stdx,stdy,stdr,rot,squint,p,l;
    int i,ngcp;
    char infile[20];           /* filename */
    char comment[80];          /* comment line */
    char line[80];             /* line of input file */
    FILE *fp, *fpout, *fopen(); /* file pointers */

    /* Type out the header message */
    printf("LSTSQR - Least Squares Solution to Image Transformation\n");

    /* Inform user of command syntax if no parameters are present */
    if (argc<=1) {printf("usage: LSTSQR gcp.dat \n"); exit(0);}

```

```

/* Change filename to uppercase */
strcpy(infile,strupr(argv[1]));

/* get name of ground control point file */
fp = fopen(infile,"r");
if (fp==NULL) {printf("Error opening %s\n",infile); exit(1);}
fpout = fopen("matrix.dat","w");
if (fpout==NULL) {printf("Error opening MATRIX.DAT\n"); exit(1);}

/* find out how many control points need to be read in */
fgets(comment,70,fp);
printf("%s",comment);
printf("{ IMAGE COORDINATES } { MAP COORDINATES }\n");
printf(" GCP LINE PIXEL EASTING NORTHING ALT\n");
ngcp=0;
while (!feof(fp)) {
    fgets(line,70,fp);
    if (!feof(fp)) {
        printf("%s",line);
        ngcp++;
    }
}
printf("# of ground control points=%d\n",ngcp);
rewind(fp);
fgets(comment,70,fp);

/* allocate memory for matrices */
ap=dmatrix(1,3,1,3);          /* A transpose times A */
bp=dmatrix(1,3,1,2);          /* A transpose times B */
b=dmatrix(1,ngcp,1,2);        /* UTM positions (transformed) */
img=dmatrix(1,ngcp,1,3);       /* Image line,pixel numbers */
code=dmatrix(1,ngcp,1,1);      /* GCP identifiers */
imgcpy=dmatrix(1,ngcp,1,3);    /* Copy of IMG */
utm=dmatrix(1,ngcp,1,3);       /* UTM positions (measured from map) */
x=dmatrix(1,3,1,2);            /* Transformation matrix */
r=dmatrix(1,ngcp,1,2);         /* displacement error (easting,northing) */

/* initialize image coordinate matrices and utm position matrices */
for (i=1;i<=ngcp;i++) {
    fgets(line,70,fp);
    sscanf(line,"%lf %lf %lf %lf %lf %lf",&code[i][1],&img[i][1],&img[i][2],
        &utm[i][1],&utm[i][2],&utm[i][3]);
    img[i][3]=1.0;
}

/* make a copy of the image line and pixel numbers */
matcpy(img, 1, ngcp, 1, 3, imgcpy);

/* multiply image coordinate matrix by its own transpose */
matatb(img,1,ngcp,1,3,imgcpy,1,ngcp,1,3,ap);

```



```

/* multiply UTM coordinates by transpose of image coordinate matrix */
matatb(img,1,ngcp,1,3,utm,1,ngcp,1,3,bp);

/* linear equation solution by Gauss-Jordan elimination, AX = B.
   a[1..n][1..n] is an input matrix of n by n elements. b[1..n][1..m] is
   an input matrix of size n by m containing the right-hand side
   vectors. On output, a is replaced by its matrix inverse, and b is
   replaced by the corresponding set of solution vectors. */
gaussj(ap, 3, bp, 2);

/* copy results to transformation matrix */
matcpy(bp, 1, 3, 1, 2, x);

/* multiply results by image coordinate matrix to yield UTM positions */
matmul(img,1,ngcp,1,3,x,1,3,1,2,b);

/* subtract from measured UTM positions to give the residual error */
matsub(utm,1,ngcp,1,2,b,r);

/* write transformation matrix to file called MATRIX.DAT */
fprintf(fpout,"%f %f %f\n",x[1][1],x[2][1],x[3][1]);
fprintf(fpout,"%f %f %f\n",x[1][2],x[2][2],x[3][2]);

/* print out some results */
printf("\n /   \ \      /   %18s \ \ /   \ \      / %12s \ \  \n"," "," ");
printf(" | X |   | %11f %11f || L |   | %14f | \n",x[1][1],x[2][1],x[3][1]);
printf(" |   | = |   %18s ||   | + | %14s | \n"," "," ");
printf(" | Y |   | %11f %11f || P |   | %14f | \n",x[1][2],x[2][2],x[3][2]);
printf(" \ \ /   \ \      /   %18s /   \ \ /   \ \ %12s /   \n"," "," ");
printf("\n\n");

/* initialize statistical parameters */
totx=0;toty=0;totr=0;totx2=0;toty2=0;totr2=0;

/* compute residual error for each point (combined direction components) */
printf("{          RESIDUAL ERROR          }\n");
printf(" GCP      EASTING    NORTHING  MAGNITUDE\n");
for (i=1;i<=ngcp;i++) {
    resd = sqrt(SQR(r[i][1])+SQR(r[i][2]));

    /* keep running totals of statistical parameters */
    totx=totx+r[i][1];
    toty=toty+r[i][2];
    totr=totr+resd;
    totx2=totx2+SQR(r[i][1]);
    toty2=toty2+SQR(r[i][2]);
    totr2=totr2+SQR(resd);
    printf("%5.0f  ",code[i][1]);
    printf("%11f %11f %11f\n",r[i][1],r[i][2],resd);
}

/* compute average displacement and standard deviation */

```

```

    avx=totx/ngcp;
    avy=toty/ngcp;
    avr=totr/ngcp;
    stdx=sqrt((ngcp*totx2-SQR(totx))/(ngcp*(ngcp-1)));
    stdy=sqrt((ngcp*toty2-SQR(toty))/(ngcp*(ngcp-1)));
    stdr=sqrt((ngcp*totr2-SQR(totr))/(ngcp*(ngcp-1)));
    printf("      =====\n");
    printf("      %11f %11f %11f  Average\n",avx,avy,avr);
    printf("      %11f %11f %11f  Standard Deviation\n\n",stdx,stdy,stdr);

    /* calculate squint angle, rotation angle, and spacing */
    rot=atan(-x[1][2]/x[1][1])*r2deg;
    squint=atan(x[2][1]/x[2][2])*r2deg-rot;
    p=sqrt(SQR(x[2][1])+SQR(x[2][2]));
    l=sqrt(SQR(x[1][1])+SQR(x[1][2]));
    printf("Rotation angle = %11f degrees\n",rot);
    printf("Squint angle   = %11f degrees\n",squint);
    printf("Line spacing   = %11f m\n",l);
    printf("Pixel spacing  = %11f m\n",p);

    /* Close all files */
    fclose(fp);
    fclose(fpout);
}

void matmul(double **a, int arl, int arh, int acl, int ach,
            double **b, int brl, int brh, int bcl, int bch, double **c) {
/* matrix multiply */

    int i,j,k;
    double x;

    if (ach-acl != brh-brl) nrerror("%matmul - matrices incompatible");
    for (i=arl;i<=arh;i++) {
        for (j=bcl;j<=bch;j++) {
            x = 0.0;
            for (k=acl;k<=ach;k++) x=x+a[i][k]*b[k][j];
            c[i][j]=x;
        }
    }
}

void matatb(double **a, int arl, int arh, int acl, int ach,
            double **b, int brl, int brh, int bcl, int bch, double **c) {
/* this routine multiplies the transpose of the first input matrix
   by the second input matrix */

    int i,j,k;
    double x;

    if (arh-arl != brh-brl) nrerror("%matatb - matrices incompatible");

```

```

    for (i=acl;i<=ach;i++) {
        for (j=bcl;j<=bch;j++) {
            x = 0.0;
            for (k=arl;k<=arh;k++) x=x+a[k][i]*b[k][j];
            c[i][j]=x;
        }
    }
}

void matcpy(double **a, int arl, int arh, int acl, int ach, double **b) {
/* this routine copies matrix a into b */
    int i,j;

    for (i=arl;i<=arh;i++) {
        for (j=acl;j<=ach;j++) b[i][j]=a[i][j];
    }
}

void matsub(double **a, int arl, int arh, int acl, int ach,
            double **b, double **c) {
/* this routine subtracts matrix b from a and writes result into c */
    int i,j;

    for (i=arl;i<=arh;i++) {
        for (j=acl;j<=ach;j++) c[i][j]=a[i][j]-b[i][j];
    }
}

/*****
RESAMP.C
*****/

#include<string.h>
#include<stdio.h>
#include<stdlib.h>
#include<stddef.h>
#include<math.h>

int main(argc,argv)

char *argv[];                /* command line arguments */
int argc;                    /* number of command line args */

{
    double m[3][3],utm_offset[3][2],easting,northing;
    double e[2],n[2];
    double grid;
    unsigned char original;
    unsigned char *res,*in;
    int i,j,iline,ipix;
    char infile[20],hdrfile[20];    /* filenames */
    char line[80];                  /* line of input file */

```

```

FILE *fp, *fpout, *fphdr, *fopen();          /* file pointers */
char *pext;                                  /* pointer to extension */
int nrows,ncols,orows,ocols;

printf("RESAMP - Image Resampler\n");

/* Inform user of command syntax if no parameters are present */
if (argc<=1) {printf("usage: RESAMP image.b01\n"); exit(0);}

/* Change filename to uppercase */
strcpy(infile,strupr(argv[1]));

/* read in transformation matrix produced by LSTSQR */
fp = fopen("MATRIX.DAT","r");
if (fp==NULL) {
    printf("Transformation matrix file (MATRIX.DAT) missing\n");
    exit(1);
}
fgets(line,70,fp);
sscanf(line,"%lf %lf %lf",&m[1][1],&m[1][2],&utm_offset[1][1]);
fgets(line,70,fp);
sscanf(line,"%lf %lf %lf",&m[2][1],&m[2][2],&utm_offset[2][1]);
fclose(fp);

/* read in output UTM boundaries and grid spacing */
fp = fopen("BOUNDS.DAT","r");
if (fp==NULL) {
    printf("UTM boundaries file (BOUNDS.DAT) missing\n");
    exit(1);
}
fgets(line,70,fp);
sscanf(line,"%lf %lf",&n[0],&n[1]);
fgets(line,70,fp);
sscanf(line,"%lf %lf",&e[0],&e[1]);
fgets(line,70,fp);
sscanf(line,"%lf",&g);
fclose(fp);

/* open imagery file */
fp = fopen(infile,"rb");
if (fp == NULL) {
    printf("%%fopen - error opening SARDN1-file (%s)\n",infile);
    exit(1);
}

/* open and read header file */
strcpy(hdrfile,infile);
pext = strstr(hdrfile,".B01");
strncpy(&hdrfile[pext-hdrfile],".HDR\0",5);
fphdr = fopen(hdrfile,"r");
if (fphdr == NULL) {
    printf("%%fopen - error opening SARDN1-header file (%s)\n",hdrfile);

```

```

    exit(1);
}
fscanf(fphdr,"FILE_TYPE          = IMAGE\n"
          "IMAGE_LINES           = %d\n"
          "LINE_SAMPLES           = %d\n"
          "SAMPLE_BITS             = \n"
          "IMAGE_POINTER            = \n"
          "END\n",&nrows,&ncols);
fclose(fphdr);

/* open resampled output file */
fpout = fopen("RESAMP.B01","wb");
if (fpout==NULL) {printf("Error opening RESAMP.B01\n"); exit(1);}

/* allocate memory for output line */
ocols = (int)((e[1]-e[0])/grid);
orows = (int)((n[1]-n[0])/grid);
printf("resampled dimension (rows x cols) = %d x %d\n",orows,ocols);
res = (unsigned char *) calloc((unsigned)(ocols+10),sizeof(unsigned char));
if ('res) {
    printf("Not enough memory for output file buffer\n");
    exit(0);
};

/* allocate memory for input file */
in = (unsigned char *) calloc((unsigned)ncols*nrows,sizeof(unsigned char));
if ('in) {
    printf("Not enough memory for input file buffer\n");
    exit(0);
};

/* read in the entire input file */
for (i=0;i<nrows;i++) {
    fseek(fp, (long)i*(long)ncols, SEEK_SET);
    fread(&in[(long)i*ncols], sizeof(unsigned char), (unsigned)ncols, fp);
}

/* loop to calculate line and pixel numbers for desired UTM coords. if
   not within the bounds of the input file, the value is set to 128 */
i=0;
for (northing=n[1]; northing>n[0]; northing-=grid) {
    j=0;
    for (easting=e[0]; easting<e[1]; easting+=grid) {
        iline=(int)(m[1][1]*easting+m[1][2]*northing+utm_offset[1][1]);
        ipix=(int)(m[2][1]*easting+m[2][2]*northing+utm_offset[2][1]);
        if (iline>nrows || iline<1 ||
            ipix>ncols || ipix<1) {
            original = 128;
        } else {
            original = in[(long)(iline-1)*(long)ncols+(long)ipix];
        }
        res[j]=original;
    }
}

```

```
        j++;
    }
    fwrite(res, sizeof(unsigned char), (unsigned)j, fpout);
    i++;
    printf("Row %d of %d\r", i, orows);
}
printf("\n");

/* open the output header file */
fphdr = fopen("RESAMP.HDR", "w");
if (fphdr == NULL) {
    printf("%s\n", "fopen - error opening SARDM1-header file (RESAMP.HDR)");
    exit(1);
}

/* Write out the SARDM1 header */
fprintf(fphdr, "FILE_TYPE      = IMAGE\n"
              "IMAGE_LINES      = %d\n"
              "LINE_SAMPLES     = %d\n"
              "SAMPLE_BITS      = \n"
              "IMAGE_POINTER     = \n"
              "END\n", 1, 1);

/* Close all files */
fclose(fphdr);
fclose(fp);
fclose(fpout);
}
```

Bibliography

Ballard, Dana H. and Brown, Christopher M.

1982 *Computer Vision*, Englewood Cliffs: New Jersey, Prentice-Hall

Bentzen, Steven

1987 *Evacuations Widespread in Perth-Andover*, Daily Gleaner (Fredericton, N.B.), 2 April, p. 1.

1987 *Spring Flooding Batters Perth-Andover*, Daily Gleaner (Fredericton, N.B.), 3 April 1987, p. 1.

Canada Centre for Remote Sensing

1988 *CCRS Airborne C/X-SAR*, Energy Mines and Resources

Curran, Paul J.

1985 *Principles of Remote Sensing*, London: Longman Group Limited.

Dahlquist, Germund, *translated by Ned Anderson and Åke Björck*

1969 *Numerical Methods*, Englewood, New Jersey: Prentice-Hall, Inc.

Doc, Major William W.

1985 *Aerial Photointerpretation and Analysis of Potential Ice Jam Sites on the Delaware River*, Proceedings of U.S. Army Corps of Engineers Fifth Remote Sensing Symposium, Volume I, Remote Sensing Applications for Water Resource Management, October 28-30, 1985. Ann Arbor, Michigan, USA, pp. 272-283.

Energy Mines and Resources

- 1980 *Grand Lake, New Brunswick* 1:50000 topographic map series sheet 21G/16.

Environment Canada

- 1974 *New Brunswick Flood, April-May 1973*, Technical Bulletin No. 81, Inland Waters Directorate, Atlantic Region, Halifax, Nova Scotia

Environment Canada

- 1984 *Flooding in New Brunswick: An Overview: 1696-1984*, Water Planning and Management Branch, Inland Waters Directorate, Atlantic Region, Halifax, Nova Scotia

Grosvenor, M.B., editor

- 1975 *National Geographic Atlas of the World, 4th edition* Washington: National Geographic Society.

Hall, Dorothy K. and Martinec, Jaroslav

- 1985 *Remote Sensing of Ice and Snow*, London: Chapman and Hall.

Hovanessian, S.A.

- 1980 *Introduction to Synthetic Array and Imaging Radars*, Dedham, Maryland, USA: Artech House, Inc.

Hoyt, William G. and Walter B. Langbein

- 1955 *Floods*, Princeton: Princeton University Press.

Imhoff, Marc L.; Vermillion, C.; Story, M.H.; Choudhury, A.M.; Gafoor, A.; and Polcyn, F.

- 1987 *Monsoon Flood Boundary Delineation and Damage Assessment Using Space Borne Imaging Radar and Landsat Data*, Photogrammetric Engineering and Remote Sensing, Vol. 53, No. 4, April 1987, pp. 405-413.

Kasischke, Eric S.

- 1984 *the Use of Synthetic Aperture Radar Imagery to Detect Hazards to Navigation*. Ann Arbor, Michigan, USA: Radar Division, Environmental Research Institute of Michigan.

Kumthekar, Madhav B. and M.A. Alasingracher

- 1985 *Some Aspects of Flood Studies of Sahibi River Basin Using Remotely Sensed Data*, from Proceedings of the Nineteenth International Symposium on Remote Sensing of the Environment, Volume II. Ann Arbor, Michigan, USA: ERIM, pp. 891-896.

Llewellyn, Stephen

- 1987 *Ice Jams Cause Minor Flooding*, Daily Gleaner (Fredericton, N.B.), 1 April, p. 19.
- 1987 *Emergency Committee Spends Busy Night*, Daily Gleaner (Fredericton, N.B.), 3 April, p. 17.

Livingstone, C.E.; Gray, A.L.; Hawkins, R.K.; Olsen, R.B.; Deane, R.A.; and Halbertsma, J.

- 1987 *CCRS C-band Airborne Radar - System Description and Test Results*, Paper prepared for the 11th Canadian Symposium on Remote Sensing (June 22-25, 1987), Waterloo, Ontario.

McCann, Douglas and Maurice Barr

- 1986 *Matching SAR Imagery with Terrain Feature Models*, from the proceedings of the Eighth International Conference on Pattern Recognition, Paris, France, October 27-31, 1986., pp. 1232-1235.

Martin, Robert

- 1987 *Hundreds Remain Homeless in N.B. as Icy Floodwaters Continue Raging*, Globe and Mail, 4 April 1987, p. A4.

Mitchell, B.

- 1978 *Physical Adjustments and Institutional Arrangements for the Urban Flood Hazard: Grand River Watershed*, Waterloo, Ontario: Department of Geography Publication No. 13, Faculty of Environmental Studies, University of Waterloo.

New Brunswick Department of the Environment, Water Resources Branch

- 1981 *1:50000 Flood Risk Map: Oromocto - Lower Jemseg Area, New Brunswick*, Derived from 1:10000 scale flood risk maps.

New Brunswick Floods Force Hundreds to Flee Along Saint John River

- 1987 *Globe and Mail*, 3 April, p. A1.

Ontario Ministry of Natural Resources

- 1984 *Ice Management Manual*, Government of Ontario.

Parashar, S.K.

- 1976 *Radar Monitoring of Lake/River Ice - State of the Art*, RSL Technical Memo, 291-4, Lawrence, Kansas: Remote Sensing Laboratory, The University of Kansas Space Technology Center., January, 1976, pp. 1-14.

Penguin Dictionary of Physical Geography

- 1984 Whittow, John, editor, Harmondsworth, Middlesex, England: Penguin Books.

Prowse, T.D.

- 1989 *Ice Break-Up On Northern Rivers: The Liard River as an Example*, from Occasional Paper No. 22: Northern Lakes and Rivers, W.C. MacKay, editor, Boreal Institute for Northern Studies, Edmonton: University of Alberta.

Ramamoorthi, A.S.; Rohinikumar, D.V.; and Manavalan, P.

- 1985 *Utility of LANDSAT-MSS Data for Flood Studies*, from Proceedings of the Sixth Asian Conference on Remote Sensing, November 21-26, 1985, Hyderabad, India: ACRS.

Rees, W.G.

- 1990 *Physical Principles of Remote Sensing*. Cambridge: Cambridge University Press.

Story, Alan

- 1987 *Mop-up Under Way as N.B. Floods End*, Toronto Star, 4 April 1987, p. A1.

Ulaby, Fawwaz T.; Moore, Richard K.; and Fung, Adrian K.

- 1981 *Microwave Remote Sensing: Active and Passive*, Volume I, Microwave Remote Sensing Fundamentals and Radiometry. Don Mills, Ontario: Addison-Wesley Publishing Company.

Ward, Roy

- 1978 *Floods: A Geographical Perspective*, London: The MacMillan Press Ltd.

Water Levels Dropping

- 1987 Daily Gleaner (Fredericton, N.B.), 4 April, p. 3.

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