Topics in Applied Interferometric SAR Research

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ABSTRACT

Airborne and satellite radar interferometry are discussed from the perspective of a commercial company supplying production mapping systems to the remote sensing community. While much progress has been made in making maps from interferometric SAR (InSAR) data, some problems have to be solved before InSAR can be used to make maps on a production basis.

In this paper, the roles of airborne and satellite InSAR are presented, and the main problems associated with each are discussed. In the airborne InSAR case, motion compensation is the most critical step. By choosing the reference tracks carefully, and by using accurate geometry models, terrain height errors due to unknown initial elevations can be minimized. The analysis allows us to specify the optimal parameters of an airborne InSAR system. In the satellite InSAR case, image registration, phase unwrapping and interferometer calibration (baseline estimation) are the most troublesome steps. A number of different approaches to each of these steps are discussed, and if possible, the best one identified. Finally, associated work in SAR processing algorithms is discussed, with an emphasis on those algorithms which preserve the phase of the image product as best as possible.

1. INTRODUCTION

As part of serving its markets in airborne and satellite radar remote sensing, MacDonald Dettwiler is conducting research into SAR interferometry. In this section, we introduce the airborne and satellite SAR programs at MacDonald Dettwiler, which illustrate how interferometry is a natural extension of these programs. A comparison of the airborne and satellite cases is given, showing how the unique properties of each case give rise to specific problems that must be solved before operational systems can be delivered.

1.1 Airborne SAR Programs at MDA

A summary of airborne radar programs at MacDonald Dettwiler is given in Table. The table shows the year of delivery, the aircraft platform type, the system designation, and comments describing the key innovation or technology. All systems include real-time digital processing, with outputs such as video displays, tape recorders and downlinks. A key technology was the introduction of digital motion compensation in 1986, with the transfer alignment option in 1991. In the latter case, a strapdown inertial reference unit (IRU) is attached to the antenna, and the alignment or navigation information is transferred from the aircraft inertial navigation system (INS).

In addition to these programs, MDA has upgraded its generalized software processor, GSAR, to process the IRIS airborne radar data, and is currently building a Unix-based software processor to serve as an interactive desktop experimental SAR processing facility.

The above programs attest to MDA's commitment to the airborne SAR remote sensing and mapping market. As the next logical step in this market, MDA is cooperating with

Table 1 - Airborne Radar Programs at MacDonald Dettwiler.

Year	*Platform*	*Radar System*	*Description*
1979	CV-580	SAR-580 (now P3-SAR)	Single-look real-time processor (RTP) with range and azimuth compression
1983	Conquest	STAR-1	RTP with 7-look azimuth compression
1986	Conquest	STAR-2	RTP with digital motion compensation
1986	CV-580	IRIS	Complete C-band SAR system
1987	CV-580	IRIS	Complete X-band SAR system
1990	Challenger	STAR-3	Dual-sided X-band SAR system (upgrade to STAR-2)
1991	CV-580	SpotSAR	Digital motion compensation with transfer alignment
1993	Learjet	NRSC	RTP for Loral X-band UPD-8 SAR

Table 2 - Satellite SAR Activities at MacDonald Dettwiler.

Year	*Program*	*Comments*
1978	SEASAT	Range/Doppler Algorithm developed, first digitally processed SEASAT image produced
1980	SEASAT	Autofocus algorithm developed
1980	ERS-1	Multi-look SPECAN algorithm developed
1982	SEASAT	GSAR commercial processor developed (20 delivered)
1984	ERS-1	Prototype satellite real-time processor delivered
1986		Doppler ambiguity resolver developed
1988	ERS-1	First ERS-1 ground station delivered (14 delivered to date)
1989		Range/Doppler algorithm made phase preserving
1990		Chirp scaling SAR processing algorithm developed
1992	ERS-1	Quicklook processor delivered (1/4 real time)
1993	Radarsat	Begin building Radarsat processor and ground station
1993	ASAR	Building prototype ASIC for SAR signal data compression

the Canada Centre for Remote Sensing (CCRS) to develop the technology for future airborne radar interferometer instruments, including experiments with the IRIS system (Gray, 1992). In addition, MDA is conducting an internal research and development program to address technical and implementation issues, which is described in Section 2.

1.2 Satellite SAR Programs at MDA

Highlights of MacDonald Dettwiler's satellite SAR programs and technologies are listed in Table 2. The focus has been on the development of accurate and efficient SAR processing algorithms, and on the production of ground stations with integrated SAR processors.

With the parallel development of ground stations for optical satellites, MDA's products are being enhanced into integrated satellite mapping and land information systems. Recognizing that the next advance in global mapping will come from satellite radar interferometry, MacDonald Dettwiler has funded a satellite interferometry research and development program, to develop algorithms and to build a demonstration interferometric processing workstation. The R & D program is outlined in Section 3.

1.3 Industrial Research Chair at UBC

Recognizing the need for additional research resources and staff training, MacDonald Dettwiler has sponsored an Industrial Research Chair at the University of British Columbia (UBC). The mandate of the chair is to do applied research in Radar Remote Sensing and Digital Signal Processing, including fields such as SAR processing, interferometry, polarimetry and SAR data compression. In April 1993, Dr.Cumming transferred to UBC as the chairholder, and Mr.Stevens and Mr.Seymour have joined the chair as postgraduate research students, working on airborne and satellite InSAR respectively. It is planned to continue the research described in this paper at UBC, with parallel development activities carried out at MacDonald Dettwiler.

1.4 Airborne vs. Satellite Interferometry

Airborne and satellite interferometry have different technologies, different design challenges and different areas of application. Some of these differences are highlighted in Table 3. Note that many parameters and features of the two systems complement each other.

The main technical differences between the two cases are dominated by the mode of the interferometer and the platform dynamics. The interferometer sensitivity and noise properties are governed by the *baseline*, the radar wavelength and the slant range. For typical radar wavelengths of C-band to X-band, the relatively short range of an aircraft SAR means that the two antennas can be mounted on the same platform (with baselines of 1 3 m), while for a satellite, the baseline requirement of several hundreds of metres means that two satellites must be used to carry the two antennas, or a single satellite used in a repeat-pass mode. The latter configuration is referred to as two-pass interferometry, and leads to the problems of temporal decorrelation, inter-channel registration and the need to estimate the baseline.

Baseline speckle can also be high when the two orbits are further apart than the desired baseline separation (Gabriel, 1988). These problems, combined with the lower SNR of satellite SARs, lead to more difficult phase unwrapping than aircraft SARs, and generally worse height estimation accuracies. For these reasons, much of the satellite interferometry research is aimed at improving the orbit estimation procedures, calibrating certain orbit variables from the received data, and better phase unwrapping procedures. This reasoning has been used to define MacDonald Dettwiler's satellite interferometry R & D program, which is described in Section.

In contrast, the main technical challenge in airborne radar interferometry comes from the irregular motion of the platform, caused by air turbulence and flight dynamics. Motion compensation systems have been used for many years to maintain image focus in the presence of flight disturbances, but with the advent of interferometry, motion compensation becomes much more critical. This is because of the higher sensitivity to phase errors in interferometry, and because of the two channels involved. MacDonald Dettwiler's R & D programs have been directed to improving the motion compensation system design and accuracy, and in developing interferometric processing algorithms which are optimized with respect to the motion compensation formulation. This R & D program is outlined in Section 3.

Currently, NASA (JPL) and the Italian Space Agency are conducting trade-off studies on a satellite interferometer for global mapping, called the Global Topography Mission (Vetrella, 1993). It is interesting to note that the trade-off studies lead to a system design that takes the best features from current airborne and satellite practice, namely:

1. no temporal decorrelation with simultaneous reception by 2 satellites,
2. good baseline control with careful orbit maintenance,
3. good baseline estimation with differential GPS,
4. higher SNR with the use of low frequencies and low altitude orbits.

Table 3 - Properties of Airborne vs. Satellite Interferometry.

Category	*Airborne case*	*Satellite case*
Interferometry mode	Dual antenna	Repeat pass
Sensor motion	Irregular	Smooth
Motion estimation	Motion compensation needed	Orbit estimation needed
Coverage rate	Low	High
Coverage location & direction	Flexible, within operational limits	Fixed by orbits
Coverage time	Flexible	Fixed by orbits
Incidence angle	Flexible	Limited choice
Relative system cost	Low	High
Incremental operational cost	High	Low
Data SNR	High	Moderate
Temporal Decorrelation	None	Yes (e.g. trees and water)
Baseline speckle	Low	Can be high
Inter-channel registration	Some difficulty	Difficult
Phase unwrapping	Some difficulty	Very difficult
Spatial resolution	5 m	20 m
Height accuracy	2 - 6 m	6 - 20 m

2. AIRBORNE RADAR INTERFEROMETRY RESEARCH

2.1 Introduction

The ability to derive digital terrain models from across-track airborne SAR interferometry (InSAR) has been of interest for some time (Graham, 1974, Madsen, 1993). The differential phase of the interferometer is measured with respect to the antenna phase centers. Therefore, appropriate conversion of this differential phase into the geometric path length difference requires accurate knowledge of the location of the phase centers of the two antennas used. Tracking the relative positions of the two antennas on the order of the carrier wavelength (a few centimeters) over an imaging mission is very challenging given the turbulent nature of aircraft flight. Furthermore, the effect on the differential phase of non-linear flights during the aperture synthesis must be understood and corrected. The primary difference between the airborne and satellite platforms is the necessity to correct for this turbulent aircraft motion. In this section, the role that SAR motion compensation plays in obtaining accurate topographic information is investigated.

Motion compensation has been known to be critical for airborne SAR for some time (Kirk, 1975, Oliver, 1989, Blacknell, 1989). The compensation usually involves modifying the received data by a resampling operation and a phase correction to make the compensated data appear as though it was generated from straight line sensor motion. Subsequent azimuth processing can then assume a flight along this defined reference track. In the interferometric SAR case, two channels of SAR data must be motion compensated to either the same reference track or to separate tracks. In addition, the accuracy of the compensation becomes more critical as not only must the two channels be adequately focussed, but the phase of the resulting images must be very precise.

2.2 Motion Compensation Issues

The physical interpretation of the differential phase depends, among other things, upon the imaging spatial resolution and the local variation of the topography. Provided the focussing is similar in each channel, and phase preserving, then the differential phase has a physical correlation to the topography. The more localized the point spread function the more local is the estimate of the terrain elevation.

Given that the phase signal to thermal noise ratio is small for typical single-look sample values, significant spatial averaging is required in InSAR to attain the required elevation accuracy, thus reducing the focusing requirements. As the local elevation variation increases, the amount of spatial averaging may need to be reduced in order to maintain adequate spatial sampling to avoid differential phase aliasing.

Since two channels are processed in a differential mode in InSAR there is an advantage in that phase errors that are common to both channels cancel out. This proves to be a very important reality of InSAR motion compensation because it is unrealistic to expect a motion compensation system to correct a single channel to the phase accuracies required for topographic extraction (on the order of 1 *degree* in the smoothed processed image). Typical single channel defocussing would cause phase errors much larger than this. Therefore, the main issues involved in InSAR motion compensation are to identify motion induced errors that affect the channels differently, as these may lead to differential phase errors. Also of concern are mechanisms that lead to distortion of the image registration.

One important example of a source of InSAR errors is the effect of the elevation of the imaged terrain on the estimation of the topography through a motion compensation/elevation coupling. This leads to a circular elevation estimation problem which will now be investigated further. For the current discussion it will be assumed that both antennas are steered perpendicular to the reference track(s) and the effects of translational and rotational motion in the cross-track plane will be analyzed. The inertial navigation data will be assumed ideal and yaw and pitch motion will be neglected.

2.3 Effects of Unknown Terrain

Accurate motion compensation requires complete knowledge of the geometry between the antenna and the ground scatterers. The slant range to the target is known from the radar timing but the elevation angle is not known as it is a function of the terrain. This leads to a flat earth assumption where the terrain is assumed to be at a defined reference level. When the terrain elevation varies from the reference level, this assumption causes phase errors along the aperture for a given scene patch, even when the antenna trajectory is parallel to the reference track. This coupling between flight motion and terrain elevation can be an important source of InSAR height estimation errors. The nature of the error depends upon the form of the flight motion.

For a typical aircraft (for example, the Convair 580) the displacement from the defined reference track can be modelled by two components: low frequency drifts and high frequency turbulence. Low frequency drifts yield displacements that are effectively constant (an offset) during the aperture synthesis and therefore lead to constant phase errors along the aperture. The low frequency motion induced height estimate errors have been analyzed (Stevens, 1993b) and found to be proportional to the displacement from the reference track(s). The impact of these errors can be reduced by segmenting the reference track(s) to follow the slowly varying drifts, but this leads to a discontinuous differential phase which complicates phase unwrapping (Madsen, 1993). An alternative solution is to interpret the differential phase in terms of the conventional path length difference phase plus an additional term due to the motion compensation error, both of which are functions of the unknown terrain elevation. This approach has been formulated for both the single reference track and dual reference track approaches (Stevens, 1993b). There are accurate approximations to the exact solutions which simplify the equations. When these errors are disregarded and rugged terrain is imaged there can be estimation errors of greater than 1 m for typical aircraft motion.

The higher frequency component of flight motion, coupled with the flat earth assumption in motion compensation, leads to phase errors that vary along the aperture (Stevens, 1993a). Through analysis and simulation (using typical CCRS C-band parameters, Table 4) the most important effects of typical flight motion (cross-track translational and rotational motion) coupled with unknown terrain elevation for InSAR have been identified:

1. Linear deviations of the flight path from the reference track (translational velocity) perpendicular to the line of sight direction, leads to azimuth shifts of the compressed response due to the linear nature of the motion compensation phase error along azimuth.
2. Translational acceleration, perpendicular to the line of

sight direction, leads to peak shape distortion (defocussing) caused by the quadratic nature of the motion compensation phase error along azimuth.

3. Rotational acceleration leads to differential phase errors.

The first two effects are experienced almost identically in each channel for purely translational motion. Table shows a summary of the typical flight motions and the associated errors.

Table 4 - Typical CCRS InSAR Parameters.

Parameter	*Typical Value*
Wavelength	55.56 mm
Altitude	6 km
Baseline Lenght	2.8 m
Baseline Angle	40°
Slant Range	10 km
Pulse Repetition Frequency	337 Hz
Processed Aperture	2.23° ~ 3 s
Range Bandwidth	25 MHz
Range Sampling Rate	37.5 MHz

The translational velocity induced azimuth shift causes an internal distortion of the registration of the generated topographic map. For example, a 0.5 m/s velocity coupled with an unknown terrain of 1 km caused a displacement of 4.5 m. A simple way to correct for this, as a post-processing step, is to estimate the shift from the elevation estimate and the known flight motion and correct the internal registration during the SAR coordinate-to-map transformation (Stevens, 1993a). The effectiveness of this approach has been verified with simulated data.

The defocussing caused by the translational acceleration coupled with the unknown terrain elevation is not correctable without iterative processing. The greater the error in the assumed terrain elevation the greater the defocusing. For example, a translational acceleration of 0.01 g coupled with unknown terrain of 1 km produced azimuth broadening of 35%. Unfortunately, large deviations of the terrain from the reference level are usually associated with rapidly varying terrain and therefore defocussing must be minimized. These conflicting effects may make iterative motion compensation necessary for accurate processing of rugged terrain if significant translation acceleration occurs during the flight.

The differential phase is more sensitive to aircraft roll than it is to translational motion. Linear and quadratic roll causes different motion compensation phase errors between the two channels. Typical linear roll (uniform angular velocity) causes different linear phase errors between channels which could cause an azimuth inter-channel misregistration. For typical linear roll of 0.2 deg/s coupled with unknown terrain of 1 km the inter-channel shift was negligible ($<\frac{1}{32}$ of a sample). Angular acceleration coupled with unknown terrain leads to differences in the quadratic phase errors between channels. For typical quadratic roll of 0.1 deg/s^2 coupled with unknown terrain of 1 km the height estimate errors was about 0.5 m. This effect is not correctable without iterative processing.

2.4 Discussion

The mandate of InSAR motion compensation is to minimize any differential phase errors or geometrical distortion that may result from the flight motion. In addition, there is a requirement for focussing based upon the amount of spatial resolution needed, which is a function of the amount of thermal noise present (spatial averaging requirement) and the local terrain variation.

Fundamental to any non-iterative InSAR system is the fact that motion compensation must be done assuming flat terrain. This assumption can lead to local registration distortion from translational velocity, defocussing from translational acceleration, differential phase errors from angular acceleration and from constant offsets from the reference track(s). The local registration distortion can be corrected as a post-processing step. The acceleration induced phase errors can only be reduced by iterative processing (some initial elevation knowledge) whereas the constant offset effects can be removed by careful interpretation of the differential phase. The effects of other flight motion on the InSAR system, such as pitch and yaw, have yet to be analyzed. In addition, the relative merit of using one motion compensation reference track for each channel or one for both, needs to be evaluated further.

Table 5 - Effects of Unknown Terrain.

Motion Type and Typical Value		*Principle Error for Unknow Terrain = 1 km*	
Translational Velocity	0.5 m/s	Azimuth Shift	~ 4.5 m
Translational Acceleration	0.01 g	Defocussing	~ 35%
Baseline Angular Velocity (roll)	0.2 deg/s	Inter-channel Azimuth Shift	negligible
Baseline Angular Acceleration (roll)	0.1 deg/s/s	Height Estimate Error	~ 0.5 m

2.5 Radar System Design Issues

After completing an error analysis of the overall interferometric SAR system, including the interferometric processing, insight is gained into which parameters of the airborne radar system design have the greatest effect on the accuracy of the InSAR-produced digital elevation model. We examined such parameters as

1. Radar wavelength,
2. Baseline length and angle,
3. Transmitted power and receiver bandwidth,
4. Antenna pattern & steering requirements,
5. Motion compensation requirements, and
6. Signal processing requirements.

After considering these issues, MacDonald Dettwiler has developed a conceptual design for an X-band airborne radar interferometer. Two 25 cm long antennas are mounted on a single horizontal backing plate, with a baseline of 95 cm. The backing plate has an azimuth drive for yaw stabilization. In addition to the GPS-aided aircraft navigation INS system, a strapdown INU is mounted on the antenna backing plate, and a motion compensation system incorporating transfer alignment is used to correct the phase of each received channel.

The system can be installed on a light aircraft, and operated at altitudes up to 12 Km. With 600 W of average power, the system has a noise equivalent σ_o of - 45 dB at 30 Km and - 36 dB at 60 Km. The range bandwidth is 80 MHz, giving a range resolution of 2 m. The sampling rate is 100 MHz, and the 8192 range cells processed give a swath width of 12 Km slant range. This swath can be placed within the slant ranges of 6 Km to 60 Km.

A quicklook SAR image is produced in real time and displayed on-board, and precision SAR processing is done on a Unix workstation on the ground. The workstation does motion compensation, SAR processing, interferogram generation, phase smoothing, phase unwrapping and height estimation. The height data as well as the SAR image is entered into a geographic data base for map generation and other applications. By analyzing the error budget of the complete system, the elevation accuracy is predicted to be better than 2 m out to 20 Km range, increasing to 3.5 m at 60 Km range.

3. SATELLITE RADAR INTERFEROMETRY RESEARCH

3.1 Introduction

MDA has developed a prototype satellite interferometry processor on a Unix platform, and has successfully demonstrated two-pass satellite SAR interferometry with SEASAT and ERS-1 data. Multipass image registration, phase smoothing, phase unwrapping and calibration issues were studied.

In this section, we briefly discuss some of the results of investigating the following main processing stages:

1. image registration and resampling,
2. phase smoothing and phase unwrapping,
3. calibration,
4. calculation of terrain height.

3.2 Image Registration & Resampling

Unlike airborne interferometry where a range-independent shift registers images sufficiently, satellite interferometry requires range-dependent pixel by pixel resampling. The first stage in image registration is estimation of the required shifts. Estimating the shift directly for every pixel in the image is too time-consuming. Usually, the relative shifts between image chips (or bulk shifts) are estimated first. Shifts at the pixel level are then estimated by interpolating the bulk shifts. An FIR filter can then be used to resample one of the images so that common ground patches lie at the same point in the image arrays used to generate the interferogram.

There are a number of different methods for estimating bulk shifts: maximizing correlation magnitude, maximizing interferometric fringe quality (Prati, 1989), maximizing fringe spectral intensity (Gabriel, 1988), minimizing phase fluctuations (Lin, 1992) and minimizing the residue counts. We have found the minimization of the residue counts as a function of relative shift an effective method of bulk shift estimation. Chips of size 64 or 128 samples are extracted throughout the image at spacings of several hundred samples. The chips are oversampled and then shifted relative to one another at spacing of roughly 1/8 of a pixel. At each shift position, the residues in a small interferogram made from the two oversampled images are counted. Minima in the residue counts as a function of the relative shift between the chips can be used to estimate each bulk shift. For all bulk shift estimation methods the initial bulk shifts must be vetted before use to ensure that the estimates are reasonable. In particular, the residue counting method can be confounded by strong linear returns extending across the image chips used for estimation of the bulk shifts. Further exploration of the connection between the residue density and coherence magnitude of the data as a function of relative shift is ongoing.

3.3 Phase Smoothing and Phase Unwrapping

The usual method for phase smoothing is averaging in azimuth and downsampling (Li, 1990). Coherent averaging of the interferometric image pixel amplitudes is a maximum likelihood (ML) estimate of constant interferogram phase if the samples are assumed to be independent (Rodriguez, 1992). The ML estimate can be thought of as averaging the complex vectors (defined by the interferogram phase) with weights proportional to the interferometric image magnitude. In principle, stronger image returns are more resistant to additive noise and therefore should provide more accurate estimates of the interferogram phase. In practice, SAR image amplitudes which differ considerably (e.g. one very strong and one weak return) may yield a similar interferometric image magnitude as two images with strong returns. We have found that phase estimates appear smoother if the image weights (the interferometric image amplitude before averaging) are based on the similarity of the individual SAR images used to create the interferogram (Seymour, 1993). The assumption of constant interferogram phase implies that low pass filtering (i.e. averaging) is a good method of estimating interferogram phase. However for scenes with rapidly varying terrain height, this assumption is not tenable and degradation of the interferogram phase estimate can be expected. For example, if the interferogram phase is locally a sinusoid with a frequency outside of the lowpass bandwidth specified by the number of samples averaged, the ML estimate assuming constant phase is clearly invalid.

After filtering, the interferogram phase must be unwrapped to calculate terrain height. Residual noise and terrain effects introduce discontinuities in the unwrapped phase surface which are dealt with by cut-line or ghost-line mapping (Goldstein, 1988, Prati, 1990). Residues lie at the end of wrap lines (places in the interferogram phase where the number of 2π wraps changes) within the image. Cut-lines join residues to limit the paths that can be taken during the unwrapping process. The limitations on the choice of phase unwrapping paths ensure that the unwrapped phase surface is consistent. It is important to note that although cut-line mapping guarantees consistency in the unwrapped phase, there is no guarantee that the unwrapped phase is correct. Manual intervention is usually required to make a reasonable set of cut-lines for an entire image. Even with manual intervention, areas with high residue density cannot be unwrapped sensibly. We mask these areas out to be interpolated after the well behaved areas of phase have been unwrapped or defined by a differently oriented data set. As noted in (Giani, 1990), areas of unwrapped phase can become isolated by unfortunate combinations of cutlines and masked out areas. Again, manual intervention is also required to offset the isolated areas of phase correctly.

3.4 Calibration and Terrain Height Estimation

Calibration refers to estimating the geometrical parameters of the interferometer:

1. the baseline distance between the satellites,
2. the angle of the baseline with respect to a reference plane, and
3. the initial slant range offset or initial off-nadir angle.

Currently, the restituted satellite orbit data is not accurate enough to give precise estimates of the interferometer geometry. Thus scene features must be used to calibrate the interferometer. Calibration in smooth terrain is reasonably easy under the assumption of flat terrain.

For variable terrain, the calibration process becomes more difficult. An error in calibration parameters may not give rise to significant errors locally but may cause significant errors in terrain height the further one is in the image from the calibration site. In addition, the nature of prominent terrain features used for calibration also impedes the calibration process.

Open water boundaries or local peaks in the topography are often used to estimate the parameters of the interferometer. These areas generally have higher average phase noise than the rest of the interferometric image. Prominent terrain features with known spot elevations are usually local peaks in the topography so phase aliasing can cause errors in calibration. Image amplitudes near or on open water boundaries likely will consist partially of echoes from the water. In two-pass interferometry, the water is uncorrelated between the passes. The resultant noise in the water boundary pixel amplitude can degrade the accuracy of the calibration process.

For small isolated portions of the FRINGE data set, we have generated fairly accurate (10 - 20 m error) estimate of the terrain height (Seymour, 1993). However, we were unable to estimate consistent parameters for the whole data set. Although we could estimate consistent calibration parameters for sites distributed in range, we were unable to estimate consistent parameters for test sites distributed in azimuth.

Preliminary investigation suggested three possible sources of the inconsistency: phase unwrapping, slight changes in the satellite orbits and azimuth Doppler centroid differences. The azimuth Doppler centroid difference does not contribute to biases in azimuth phase. Rather, the difference in Doppler centroid contributes to noise in the interferometric image in much the same way as the range spectral shift (Prati, 1992). A change in orbit parameters across the scene is unlikely the source of the error because other terrain height estimates using ERS-1 data at similar latitudes have no evidence of this problem (Zebker, 1986). We expect that some discontinuities in azimuth phase were smoothed away by the averaging process used to eliminate noise prior to phase unwrapping. Work is ongoing to make a ML estimate of the interferogram phase using a more general phase model that will preserve large local variations in the interferogram phase.

3.5 Future Work

In the short term, final calibration and processing of the FRINGE data set is a priority. This is a particularly challenging data set because of the variable nature of the topography. It provides a challenging image for testing the capabilities of an interferometric SAR processor.

In the long term, further research in satellite interferometry will include:

1. examining RADARSAT data for interferometric applications,
2. investigating alternative calibration methods,
3. investigating alternatives to cutline mapping in phase unwrapping,
4. exploring coherence magnitude as a source of alternative information for processor verification and calibration.

4. SAR PROCESSOR DEVELOPMENT

As interferometry presents a more demanding accuracy requirement than many other SAR applications, the fidelity of SAR processing must increase. This particularly applies to phase and registration accuracy, each of which play an important role in the InSAR error budget.

Resolution, sidelobes and radiometric linearity are also important.

It is important that phase be consistent from cell to cell, so that the processor does not introduce a phase modulation depending upon which cell (or fractional cell) a particular reflector lies in. In other words, target phase should be a function of slant range only, and invariant to shifts in the processed swath or the reference range or Doppler selected for the processing parameters. All MacDonald Dettwiler's precision processors have recently been upgraded to achieve this phase invariance, mainly through careful matched filter design. In the commonly-used range/Doppler processors, more accurate range/azimuth cross-coupling terms are used in the matched filter design (Wong, 1989).

The most interesting new development in precision SAR processing has been the Chirp Scaling algorithm. In this algorithm, range cell migration correction (RCMC) is done with a phase multiply rather than the traditional interpolator (Cumming, 1992, Runge, 1992, Raney, 1993).

The method makes use of the linear FM property of the transmitted range chirp, applying a range-variant modulation to scale the data in the range direction as a function of azimuth frequency. Removing the RCMC interpolator preserves more range and azimuth bandwidth, resulting in a resolution improvement of about 3% (Wong, 1993). The signal phase is matched more closely in the various matched filtering operations, leading to better registration and phase accuracy.

The chirp scaling algorithm is more tolerant to squint than the range/Doppler algorithm, because operations performed in the two-dimensional frequency domain provide better phase matching, particularly in the azimuth-frequency dependent cross-coupling terms. In addition, a recent improvement to the chirp scaling algorithm maintains image and phase fidelity for squint angles up to 30 and higher (Davidson, 1993).

CONCLUSIONS

This paper has described a number of research and development activities that are aimed at bringing radar interferometry from the experimental to the operational stage. Specific issues in airborne radar and satellite-borne radar have been tackled with a view to understanding the factors that drive the height estimation error budget.

In the case of airborne radar, the work to date has concentrated on motion compensation, as it is one of the most challenging aspects of airborne radar processing, and because interferometry requires a different approach. It has been found that there is an interesting connection between assumed terrain height and flight motions, to the extent that an iterative approach to motion compensation and height estimation is sometimes needed to achieve the highest accuracy inherent in the data set.

In the case of satellite-borne radar, phase errors and residues due to poor image registration and incorrect phase unwrapping continue to be the limiting factor in repeat-pass interferometry. Better resampling and phase smoothing techniques have been sought to improve interferogram accuracy.

With improvements made in these areas, it is expected that radar interferometry will provide operational mapping systems in the near future. In both airborne and satellite cases, purpose-built systems planned for the future are expected to yield terrain height estimates of usable accuracy.

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