Using Ortho-Rectified SAR Imagery Acquired Over Rugged Terrain for Thematic Applications in Glacier Hydrology

by

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RÉSUMÉ

L'utilité de l'imagerie radar à synthèse d'ouverture (RSO) pour les applications thématiques en hydrologie glaciaire, telles que la cartographie de la neige et de la glace, dépend de la correction géométrique adéquate des images. La rectification des erreurs géométriques sur les images radar des régions montagneuses est souvent difficile en raison des distorsions importantes engendrées par la sensibilité du capteur au relief topographique local. Utilisant une méthode qui intègre l'information sur l'orbite du satellite et sur le capteur, des points de contrôle au sol et des données numériques d'élévation, deux images RSO de ERS-1, de Place Glacier, C.-B., sont ortho rectifiées avec succès. La localisation des lignes de neige et des limites du glacier déterminée à partir de l'imagerie RSO se situe entre 50 à 75 m de la localisation réelle basée sur les données dérivées des levés de terrain. Des estimations dérivées par satellite de mesures conventionnelles en hydrologie glaciaire, telles que la position de la ligne d'équilibre, le bilan net de masse et la superficie de la zone d'accumulation, démontrent la fiabilité de la restitution de l'ortho-rectification.

SUMMARY

The utility of Synthetic Aperture Radar (SAR) imagery for thematic applications in glacier hydrology, such as snow and ice mapping, is dependent upon proper geometric correction of the imagery. Rectifying geometric errors in radar imagery of mountainous areas is often difficult because of significant distortions arising from the sensor's sensitivity to local topographic relief. Using a method which integrates the satellite orbital and sensor information, ground control points, and digital elevation data, two ERS-1 SAR images of Place Glacier, B.C. are successfully orthorectified. The snow line positions and glacier boundary identified on the SAR imagery are within 50 to 75 m of their true locations based on data derived from field work. Satellite derived estimates of common measurements made in glacier hydrology, such as equilibrium line altitude, net mass balance, and accumulation area ratio, illustrate that the restitution accuracy of the ortho-rectification is very reliable.

INTRODUCTION

The snow line is defined as the location where there is enough snowfall and energy available to balance accumulation and ablation. Its position is a desired parameter for many applications in alpine hydrology and glaciology. For example, the snow line plays a significant role in the energy balance of a glacier basin, which in turn controls the timing and quantity of melt. Brugman (1991) has shown that during late summer the low albedo of glacier ice and firn causes two to three times more energy to be absorbed at the surface than if it were snow covered. Therefore, as the snow line position strongly affects the amount of seasonal melt discharge, it is necessary to map its location for hydrological modelling in alpine areas.

The snow line at the end of the ablation season is roughly equal to the equilibrium line altitude (ELA) for temperate glaciers (Paterson, 1994). Above the ELA a glacier has a net gain in mass over the year and below it a net loss. The ELA can be used to estimate the net mass balance of a glacier (Østrem, 1973; 1975) and provides information on large scale glacier fluctuations.

Areas of extensive alpine snow and ice accumulation are typically remote making it difficult to map features such as the snow line. Satellite imagery from VIR (Visible and Infrared) sensors can be used but cloud cover, shadows, and darkness in polar regions restrict the opportunity to obtain timely data. Spaceborne synthetic aperture radar (SAR) imagery is potentially useful since it can be acquired independent of weather and time of day with a spatial resolution compatible with the variation in alpine regions, typically less than 50 m. Measurement of hydrological parameters in mountainous regions by active microwave sensors are seriously affected by geometric and radiometric distortions caused by the sensor's sensitivity to local topographic relief. These effects must be minimised in order to extract spatially referenced information from SAR data or accurately co-registering SAR with other image data (Toutin, 1995).

In this paper we successfully map hydrological / glaciological features on ortho-rectified SAR imagery of a glacier basin. The features include the snow line position and glacier ice extent, which are used in a variety of hydro-glaciological applications. Results of the rigorous geometric correction model applied to ERS-1 SAR imagery of rugged terrain are presented. The model is based on an algorithm which estimates the geometry and residual motion of the satellite using ephemeral orbital information and ground control points (GCPs). It is then integrated with a digital elevation model (DEM) to create an ortho-image by positioning each pixel into it's true location in a user defined cartographic system.

EXPERIMENTAL DATA

The area under study is the Place Glacier Basin (50° 26' N, 122° 36 W) located in the Coast Mountain Range approximately 140 km Northeast of Vancouver, British Columbia. The basin area is 6.7 km^2, of which the glacier occupies about 55 %, with basin elevations ranging from 1820 m above sea level, at the glacier outlet stream, to a peak of 2610 m. Place Glacier has been studied and monitored since 1965, the beginning of the International Hydrological Decade (Mokievsky-Zubok and Stanley, 1976), and continues to be a important site for studies in glacier mass balance studies (e.g. IAHS (ICSI)/UNEP/UNESCO, 1994).

A DEM of the Place Glacier Basin was generated from contour lines, digitised from a 1:50,000 map sheet with a 100 foot contour interval, and point survey data using the conic search grid interpolation procedure (Carrara, 1986). The DEM has a grid spacing of 25 m and the error is estimated at ±30 m in both horizontal and vertical dimensions which mainly reflect the errors of the input data (Adam, 1996).

Two multi-look detected (3-looks) ERS-1 SAR images in ground range presentation were available for this study. They were acquired on a descending orbit for August 28 and October 2, 1992 at 12:02 Pacific Standard Time. The images each span 100 km by 100 km and cover the same area, with a resolution of 33 m in range, 30 m in azimuth, and 12.5 m pixel spacing. Using the DEM and a simple cosine back-scatter model, the topographically induced radiometric distortions were normalised prior to the geometric correction procedure to accurately identify surface cover types (Adam *et al*., 1997). The surface was divided into wet snow, glacier ice, and bedrock. Fortunately, only about 10 % of the glacier was affected by layover, which can impose serious limitations on the use of SAR data in mountainous areas (Rött, 1984), therefore nearly the entire surface could be mapped .

Data used to assess the ortho-rectification results include the snow line position on each image day, derived from daily photos of the glacier taken with a 35 mm camera, and the glacier boundary surveyed in 1994. Although the SAR images are from 1992, the glacier terminus position, which can fluctuate dramatically from year to year, changed less than two SAR pixels over those two years according to field surveys. The error of the snow line vectors is estimated to be within 25 m (two pixels), based on errors in plotting the August 28 and October 2 snow line positions onto a 1:10 000 scale map of Place Glacier.

GEOMETRIC CORRECTION MODEL

The geometric correction model was originally developed for SPOT-HRV (Toutin, 1985), and later modified for other data (VIR, SAR, spaceborne, airborne) (Toutin, 1995). The geocoding procedure using this geometric correction model has two main components (**Figure 1**): data acquisition (image, ephemeris data, GCPs) with the computation of the satellite model, and rectification of the image with a DEM.

SATELLITE MODEL

Three sources of information are required to compute the satellite model (Step 1, **Figure 1**): A full SAR scene, satellite ephemeris data, and GCPs in user defined ground coordinates. The ephemeris data are provided within the image tape header of slant range or ground range SAR image products and includes orbital, sensor, and Earth model information. For this study the

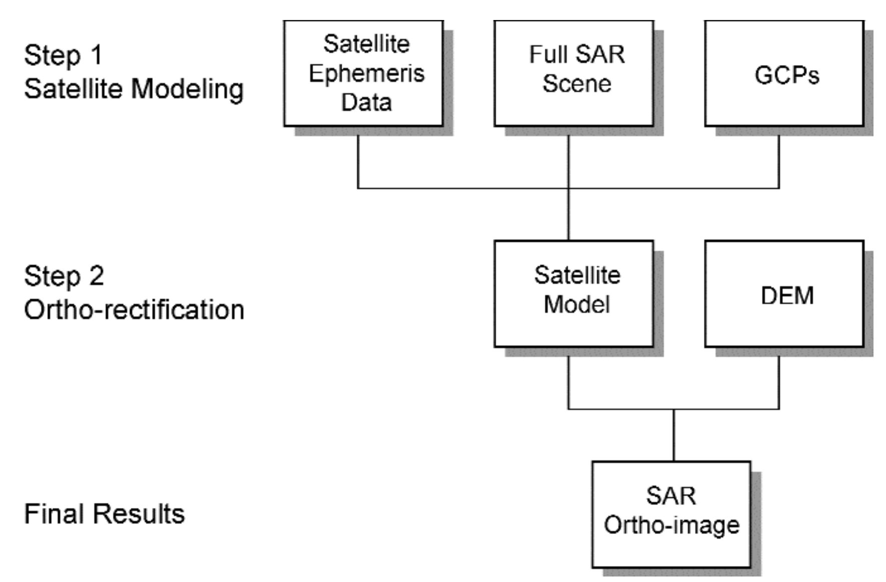

Figure 1.
Basic Components of the Geometric Correction Model.

Earth model is based on the Clarke 1866 ellipsoid. Essentially, the model accounts for and integrates the entire viewing geometry of the satellite (velocity, position), the sensor (orientation, angle, time), the Earth (curvature, rotation, elevation), and the cartographic projection. Although some of these parameters (e.g. the velocity of the satellite, orientation of sensor, and Earth's curvature) are normally corrected by SAR processor algorithms, this model assumes and corrects the presence of some geometric error residuals (Toutin, 1995).

GCPs are located over the full SAR scene since the satellite ephemeris data describes the whole image. Points are distributed near the edges and corners of the imagery and at the lowest and highest elevations to avoid extrapolation. Other points are distributed throughout the image. The GCPs used in this study include points digitised from 1:50,000 scale map sheets and 1 survey point. Control points digitised from the map sheets have an error of about 30 m in planimetry and altimetry. This is not optimal, but is sufficient for the model and expected results with satellite SAR (see Toutin, 1995).

SAR Image Ortho-rectification

The final step in the geometric correction is to rectify the image using the previously computed satellite model and a DEM to produce an ortho-rectified image in which each pixel is referenced to the ground reference system defined by the GCPs (Step 2, **Figure 1**). The resampling method used is the zero-order, nearest-neighbour interpolation.

Since the geometric model considers the distortions caused by elevation, a DEM is used to create a more precise ortho-image. Therefore, the size, resolution, and topographic fidelity of the DEM is reflected in the final ortho-image. A planimetric error of about 60 m on the SAR ortho-image is expected from a DEM with a 30 m error. This is based on a planimetric plotting error ratio of 2.1 computed for ERS-1 SAR imagery (Toutin, 1995). As the DEM is the major source of error in this particular geocoding process, a planimetric error of approximately 60 m will result regardless of the positional accuracy of the GCPs. Therefore, we expect the snow line and glacier ice extent to be within about 60 m of their true position.

Results

It has been shown that a large number of independent check-points (around 30 or more) provides an accurate assessment of the restitution accuracy (Toutin, 1995). Since a significantly greater number of points are difficult to locate, due to the remoteness of the image area, an estimate of the final ortho-rectification accuracy is available using the residuals from the GCPs (**Table 1**). As the residuals are of the same order of magnitude as the GCP error (30 m), the satellite model fits the viewing geometry of the SAR images and should not induce significant errors (Step 1). This model corrects the image globally, and not locally at the GCP locations, therefore each residual reflects the position of each GCP. Because the model is stable no trends or systematic errors are introduced.

Table 1.
Geometric correction model residuals and RMS error for each image.

ERS-1 Image	# of GCPs	Residual *x* (m)	Residual *y* (m)	RMS *x,y* (m)
August 28/92	13	25	24	35
October 2/92	12	33	30	45

Snow line and glacier outline vectors overlaid onto each ortho-image (**Figures 2a and 2b**) lie within 50 and 75 m (four and six pixels) of the wet snow - glacier ice boundary (i.e. the snow line) for the August and October ortho-images respectively (**Table 2**). The 1994 glacier outline is within 50 and 75 m (four and six pixels) of the glacier - bedrock boundary on the August and October images respectively (**Table 2**), although in some places the boundary is difficult to locate due to pixel saturation caused by slopes facing directly at the sensor. These results agree with the estimated planimetric plotting error (about 60 m) of the ortho-image caused by the 30 m DEM error, mentioned in the image ortho-rectification section (Step 2). It is evident in **Figure 3** that the residual errors incurred during rectification have not seriously affected the position of features in the basin. For example, Place Glacier is properly positioned within the valley as is the snow line in the upper basin, and the east facing slopes affected by layover are visible as saturated surfaces.

Since mid - October was the end of the ablation season in 1992, the snow line derived from the October 2 image can be compared to the published 1992 ELA for Place Glacier. The average snow line elevation, based on the DEM, for the October ortho-image is 2240 m, compared to the measured ELA of 2250 m (IAHS (ICSI)/UNEP/UNESCO, 1994) (**Table 2**). Because the upper basin of Place Glacier, where the accumulation area is found, has an average slope of 12°, the estimated planimetric plotting error of about 60 m would result in a maximum vertical error of ±12.75 m based on the ELA (2240 m) derived from SAR data and our DEM .

The ELA can be used to estimate the net mass balance (***b***) of a glacier using a linear relationship if detailed mass balance measurements are available over several years (Østrem, 1973; 1975). Using a regression equation, computed from 27 years of ELA and net mass balance data ($r^2 = 0.91$), the computed value *b* from the SAR derived ELA is -0.72 m of snow water equivalent (SWE) compared to -0.79 m SWE measured. The difference of 0.07 m SWE equates to about 250 m^3 of water, which is less than 1 % of the total volume of melt water from the basin in 1992. Although the net annual mass balance is only an approximate measure of annual melt water yield it does provides valuable information on the climatic response of a glacier during that year.

In addition to the ELA, the accumulation area ratio (AAR) is commonly used to assess the health of a glacier. The AAR is the area of accumulation (above the snow line) at the end of the ablation season divided by the total glacier area. An AAR of 0.7 roughly corresponds to a net mass loss of zero (Glen, 1963) while values below this indicate mass lost by the glacier. Using

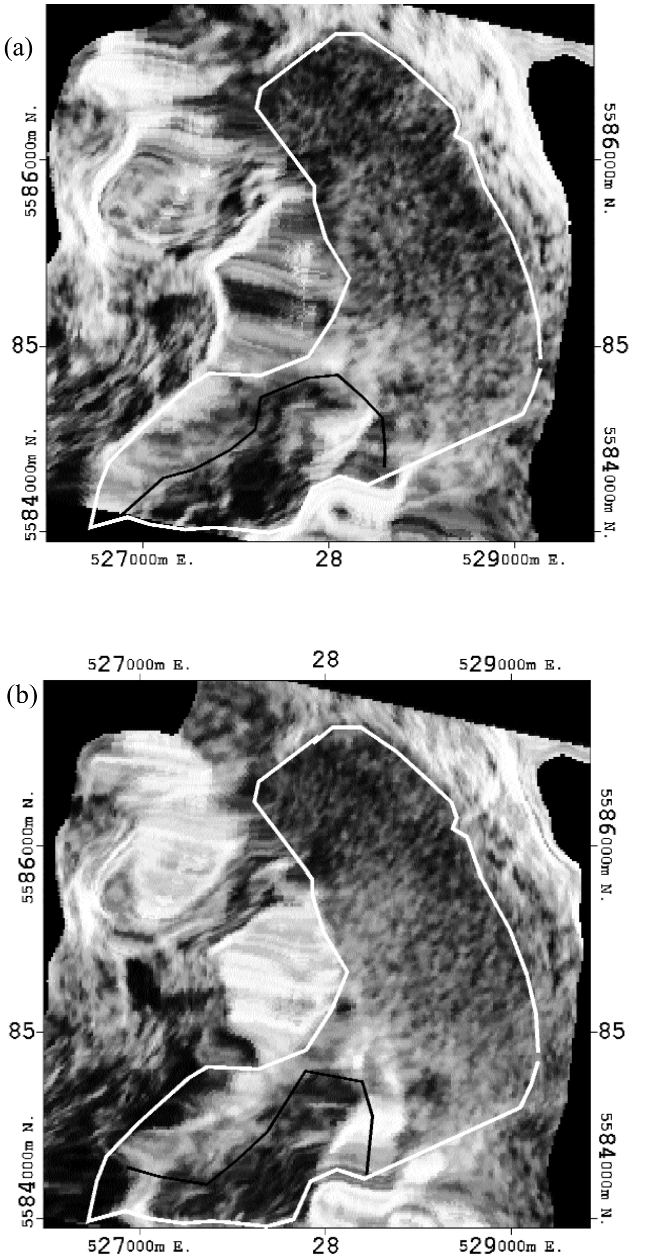

Figure 2.
Ortho-rectified ERS-1 SAR image of Place Glacier, B.C., for a) August 28, 1992 and b) October 2, 1992. The glacier outline (white line) and snow line (black line) vectors are derived from field data. The snow line is the boundary between the wet snow (low return) and glacier ice (medium return) while the high return areas are predominantly bedrock. The satellite was on a descending orbit (top of page to bottom) looking to the right.

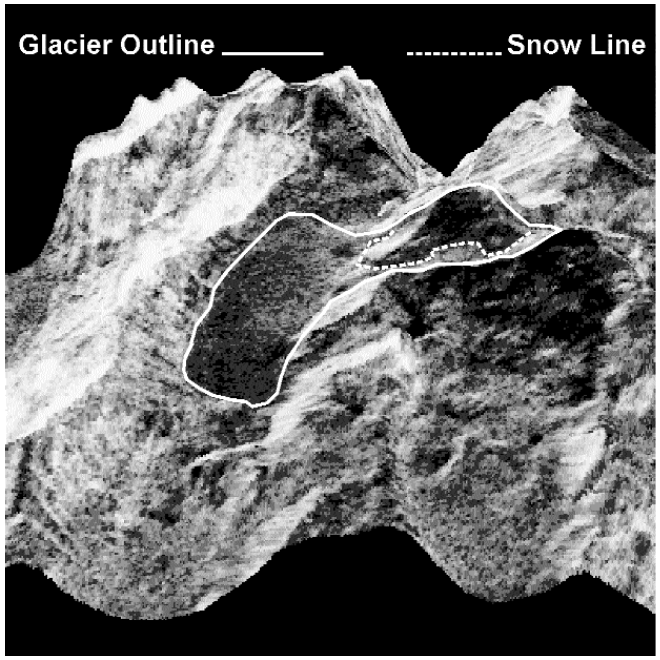

Figure 3.
Perspective view of the Place Glacier Basin generated from the DEM and the August 28, 1992 ortho-image looking north to south. The glacier falls properly within the valley and the accumulation area and snow line are correctly positioned in the upper basin of the glacier.

the area above the SAR derived snow line (approximately 0.783 km^2) and glacier boundary (approximately 3.6 km^2) the AAR is 0.20, compared to the measured value of 0.25 (IAHS (ICSI)/UNEP/UNESCO, 1994). This suggests an over estimation in glacier area of 0.6 km^2 or an under estimation in accumulation area of 0.1 km^2, but is largely the latter since the 1994 surveyed glacier boundary was approximately 3.45 km^2. Regardless, the computed AAR provides an indication of the large mass loss for that balance year, showing that about 80 % of the glacier area lost mass.

CONCLUSIONS

The utility of data obtained from active microwave sensors for thematic applications depends upon accurate geometric correction which is difficult in mountainous regions. By integrating a mathematical model for geometric correction with a DEM, two ERS-1 SAR images are successfully ortho-rectified to a UTM cartographic system.

We have estimated that the snow line and glacier boundary identified on the ortho-images differ from vector check data by 50 to 75 m. These results agree with the estimated planimetric plotting error (about 60 m) of the ortho-image, caused by the 30 m DEM error mentioned in the image ortho-rectification section (Step 2). It has been

Table 2.
Comparison of field data and SAR image derived features.

ERS-1 Image	Snow Line Error (m)	Glacier Outline Error (m)	ELA92 Error (m)	b92 Error (mSWE)	AAR92 Error
August 28/92	50	50	Not Applicable	Not Applicable	Not Applicable
October 2/92	75	75	10	0.07	0.06

demonstrated that a geocoding accuracy of 75 m or better are reliable for mapping hydrologicaly significant surface features such as the snow line and glacier ice extent in rugged terrain using satellite SAR. This level of accuracy permits hydrologists to estimate glacier basin parameters such as the equilibrium line altitude and accumulation area ratio which can be used to compute the annual net mass balance and potential water yield for glacierised areas. As the DEM was the largest source of error in this ortho-rectification procedure, positional accuracy on the ortho-image can be improved by using a DEM with resolution finer than that available on 1:50 000 mapsheets and greater horizontal and vertical accuracy (> 30 m).

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