Stereo RADARSAT for Mapping Applications*

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ABSTRACT: *RADARSAT stereoscopic images are evaluated for mapping applications in terms of planimetric and altimetric feature extraction. The first requirement is GCP collection with stereoscopic plotting. Using the monoscopic method, artificial parallaxes in GCP image co-ordinates will propagate through the entire extraction process. In fact, DEM accuracy can be improved by a factor of 20-40% when using stereo plotting. Accuracy of planimetric features (e.g. roads) extracted from an F1-F5 stereo pair is in the order of one resolution cell. Errors with 90% confidence are less than two resolution cells for DEMs extracted from nine stereo pairs (fine, standard, extended high). General guidelines are drawn for selecting a tradeoff between geometric and radiometric disparities and RADARSAT stereo pairs as a function of the relief.*

I INTRODUCTION

In the 1960's, stereoscopic methods (La Prade, 1963) were first applied to radar images to derive ground elevation leading to the development of radargrammetry. Unfortunately, research uncovered contradictions and a dichotomy between error propagation theory and practical results, particularly over high relief areas (Leberl *et al.*, 1988). These contradictions combined with the lack of stereo radar pairs led to the relative decline of radargrammetry.

The launch in 1995 of Canada's first earth observation satellite, RADARSAT with the various operating modes of the Synthetic Aperture Radar (SAR) and its specific geometric characteristic (Parashar *et al.*, 1995) has turned the tide. It is the first commercial radar system from which true stereoscopic images can be generated from its wide range of incidence angles (from 10º to 60º).

Radargrammetry has once more become a hot R&D topic. Unfortunately, it is only used for digital model elevation (DEM) extraction. By analogy with photogrammetric methods, it also can be used to extract planimetric features on a digital stereo workstation. Subtle features not discernible in a single SAR image

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are often recognized in stereo images. Furthermore, this method has been proven to be more accurate, since the feature positioning is not affected by any error in elevation (the operator plots at the vertical of the point) (Toutin, 1997a). With ortho-image generation, the DEM error propagates through the rectification process and planimetric feature extraction with a ratio of one to five depending on the SAR look angle.

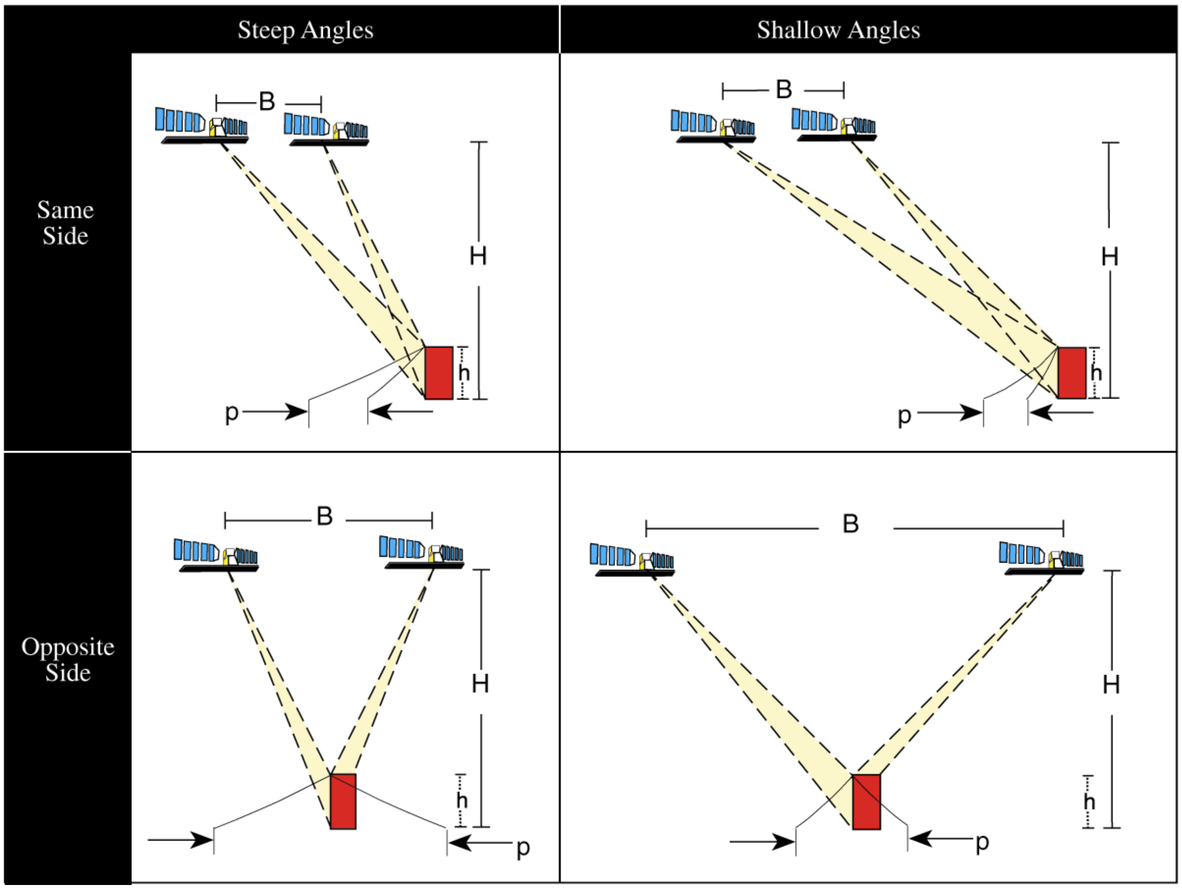

Figure 1: Various configurations of RADARSAT-SAR stereo pairs (same and opposite sides; steep and shallow look angles).

However, stereoscopy using SAR data is more problematic than visible-and-infrared (VIR) stereoscopy, which emulates human stereo vision. An *a priori* understanding of the physical components of stereo SAR is a pre-requisite to resolve the previously mentioned contradictions before any processing and planimetric and altimetric information extraction.

The objectives of the paper are then to evaluate various RADARSAT stereo-configurations (Figure 1) and the accuracy of the stereo extracted data as a function of different geometric and radiometric parameters. Using a SAR parametric solution already developed and tested at the Canada Centre for

Remote Sensing (CCRS) (Toutin, 1995) ported into a digital stereo workstation, the DVP, and a digital image analysis system, PCI, the processing errors of planimetric features and DEM extraction are analyzed and quantitatively evaluated. Geometric versus radiometric disparity tradeoffs and general guidelines for selecting RADARSAT stereo-pairs are finally suggested based on our results.

II RADARSAT FOR STEREOSCOPY

Historically, the assessment of different radar stereo viewing strategies was impeded by a lack of suitable stereo data sets. Before RADARSAT, no satellite, and only a few airborne radar systems provided data over a broad range of viewing geometry for which this tradeoff could be quantitatively analyzed. RADARSAT, which acquires imagery from a broad range of look directions, beam positions and modes at different resolutions meets this need.

As a result, researchers at CCRS have undertaken an exhaustive study under the Applications Development and Research Opportunity (ADRO) program sponsored by the Canadian Space Agency to evaluate the parameters, which enable a quantitative understanding of radar stereoscopic applications.

Twelve RADARSAT images of the Sherbrooke region, Quebec, Canada were acquired. The relief of the region is moderate with a 450-m elevation range and up-to-30° slopes (Figure 2). Table 1 summarizes the general characteristics of the images. They are a good representative set of the most used RADARSAT images: ascending (asc.) and, descending (desc.) orbits, various modes (fine, standard, extended), beams and look angles (20º to 60º). The images are in ground range presentation, orbit oriented, coded in 16 bits without any radiometric processing. Nine different stereo configurations have thus been generated and studied in detail: fine or coarse resolution, small to large intersection angle (8º to 89º) with steep or shallow look angles, with or without speckle filtering (for the fine mode).

By analogy with photogrammetry, the criterion used to analyze a stereo configuration and its potential elevation accuracy is the intersection angle ($\Delta\theta$) or its equivalent base-to-height ratio (B/H). However, as outlined in Figure 1:

1. For same side stereo, the same $\Delta\theta$ or B/H generates a larger elevation parallax with steep look angles than with shallow look angles; and
2. For opposite side stereo, a small $\Delta\theta$ or B/H with steep look angles generated a larger elevation parallax than a large $\Delta\theta$ or B/H with shallow look angles.

It is thus the reverse of VIR stereo images. In fact, the elevation parallax with SAR ground range stereo images can be approximated by: $p = h\,[\cot\theta_R - \cot\theta_L]$ (1),

Where p is the elevation parallax, h the elevation of the target, θ_R and θ_L the look angles of the right and left images, respectively.

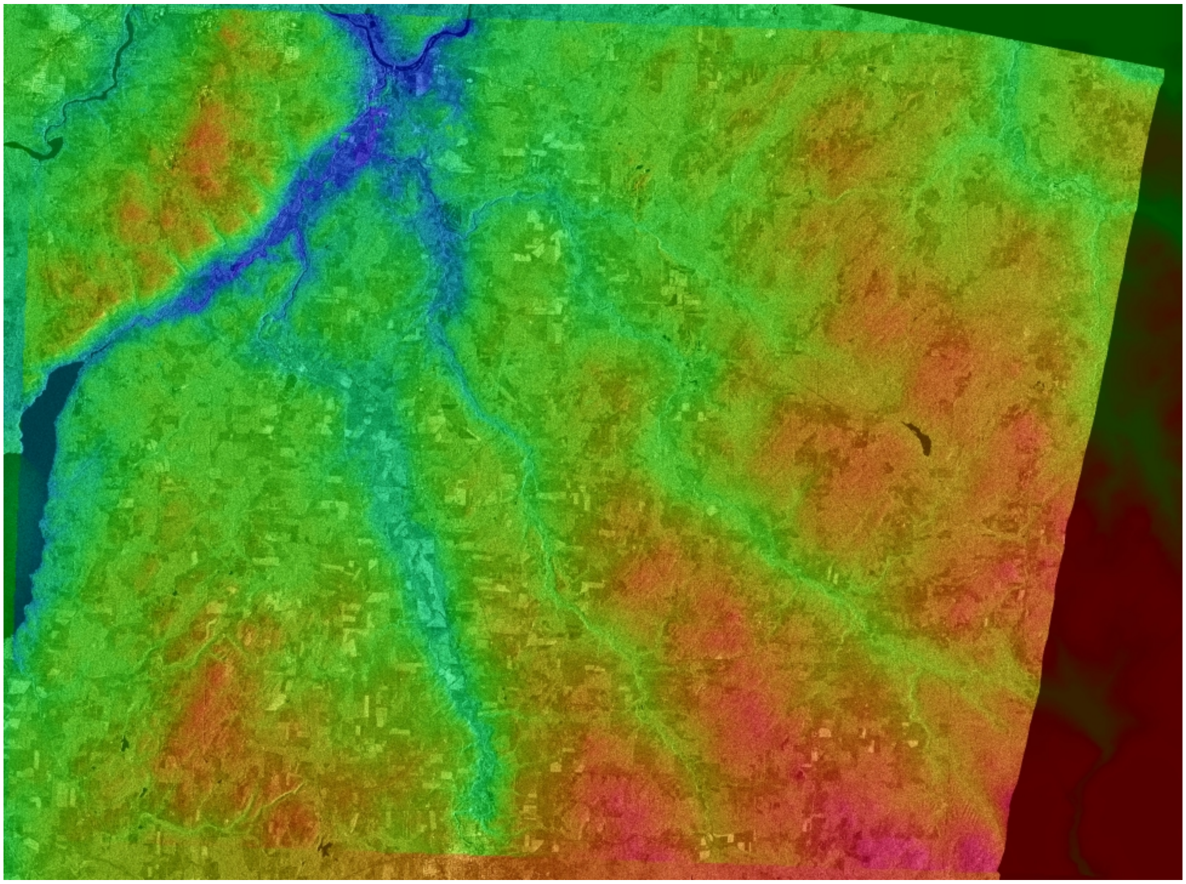

Figure 2: 3D chromo-stereoscopic image of the Sherbrooke region, Canada. The DEM is colour-coded into the RADARSAT fine mode (F4 descending) SAR ortho-image: blue for the lowest elevation and red for the highest. The Canadian Space Agency sponsored the RADARSAT image.

Table 1: General characteristics of the RADARSAT images data set.

Mode and Beam	Acquisition Date	Orbit Path	Look Angle (degrees)	Ground Coverage (km)	Ground Resolution (m)	Pixel Spacing (m)
Fin F1	20/10/96	Asc.	37° - 40°	50 x 50	9.1 x 8.4	6.25 x 6.25
Fin F2	21/10/96	Desc.	39° - 42°	50 x 50	8.7 x 8.4	6,25 x 6.25
Fin F4	04/10/96	Desc.	43° - 46°	50 x 50	8.1 x 8.4	6.25 x 6.25
Fin F5	08/06/96	Asc.	45° - 48°	50 x 50	7.8 x 8.4	6.25 x 6.25
Standard S1	24/10/96	Desc	20° - 27°	100 x 100	26 x 27	12.5 x 12.5
Standard S2	03/11/96	Asc.	24° - 31°	100 x 100	22 x 27	12.5 x 12.5
Standard S4	14/10/96	Desc	34° - 40°	100 x 100	25.7 x 27	12.5 x 12.5
Standard S5	24/05/97	Asc.	36° - 42°	100 x 100	24.2 x 27	12.5 x 12.5
Standard S7	10/05/97	Asc.	45° - 49°	100 x 100	20.1 x 27	12.5 x 12.5
Standard S7	22/10/96	Desc	45° - 49°	100 x 100	20.1 x 27	12.5 x 12.5
Extended H3	04/04/97	Desc.	52° - 55°	75 x 75	19.1 x 27	12.5 x 12.5
Extended H6	12/01/97	Desc.	57° - 59°	75 x 75	18.0 x 27	12.5 x 12.5

Consequently, the vertical parallax ratio (VPR) p/h seems to be a better criterion with SAR stereo images than the traditional intersection angle $\Delta\theta$ or base-to-height ratio B/H used with VIR stereo images.

III EXPERIMENT

The geometric modeling use in this experiment is a CCRS developed parametric model already tested on different data sets. The stereo model set-up, based on this parametric model, is the mathematical reconstruction of the three-dimensional terrain model. It is computed with ground control points (GCPs), acquired in monoscopic or stereoscopic plotting. More details on the geometric model can be found in (Toutin, 1995).

The planimetric feature extraction follows the stereo model set-up. It is done with the digital stereo workstation, the DVP, developed in collaboration between Laval University, Quebec, Canada, and CCRS and adapted for SAR images at CCRS (Toutin, 1996; 1997b). To date, the only stereo pair evaluated is F5-F1. The stereo extracted features (mainly the roads) are thus compared with the digital topographic maps (accuracy of 5 m) in the ESRI geographic information system. The main advantage of the stereo viewing is that it improves the location of ground points and the extraction of information by integrating the simultaneous plotting, the general relief perception and the backscatter of both images, since it combines both geometric and radiometric aspects.

The automated matching solution chosen for DEM extraction and adapted in the digital image analysis system, PCI, is a multi-scale area correlation with the maximum of a correlation coefficient (PCI, 1998). To evaluate the error of this processing step, elevation points were extracted every two pixels on the full study site (4 to 5 000 000 points) from nine different stereo configurations. To avoid interpolation error, they are directly compared with the 5-m accurate DEM derived from 10-m contour lines of the 1:50 000 topographic maps. Furthermore, two sub-areas of the study site were selected to see the impact of the terrain relief: one with low relief (slopes from 0º to 10º), the other with medium relief (slopes from 10º to 30º).

IV RESULTS AND DISCUSSION

IVa *Stereo model set-up results*: The first interesting result is related to the first part of this ADRO research on the localization accuracy of RADARSAT images (Toutin, 1998). It is worthwhile to mention it, since it has an impact on the full processing. Plotting the GCPs in monoscopy for both images generates errors in the stereo model set-up two to four times larger than plotting them in stereoscopy. Since the monoscopic plotting on SAR images is about 1-2 pixels it generates an artificial parallax in the stereo model, which propagates through the DEM extraction. True stereoscopic plotting enables a better relative correspondence of the GCP between the two images. Comparison of the extracted DEM using the two GCP collection methods (mono and stereo) gives the linear errors with 90% of confidence (LE90) for two stereo pairs:

1. F5-F1: 30 m for the monoscopic plotting and 25 m for the stereoscopic plotting;
2. S1-S7: 24 m for the monoscopic plotting and 14 m for the stereoscopic plotting.

The improvement for both images is in the same order relative to the resolution (7-9 m for fine mode versus 20-26 m for standard mode) and to the plotting accuracy. It thus confirms the importance of the GCP collection with stereoscopic viewing to avoid the error propagation of artificial parallaxes of GCP image co-ordinates.

IVb *Road extraction results*: The roads were separated into four categories: highway, main roads (two and more hard-surface all-weather lanes), secondary roads (two and more loose or stabilized lanes), and city streets. The results are given for 68% and 90% confidence circular errors (CE68 and CE90):

1. For highway: CE68 = 6 m and CE90 = 12 m;
2. For main roads: CE68 = 10 m and CE90 = 20 m;
3. For secondary roads: CE68 = 11 m and CE90 = 24 m; and
4. For city streets: CE68 = 9 m and CE90 = 17 m.

The errors are quite similar for the different categories: about one resolution cell for CE68, and two to three for CE90. The main differences can be accounted first for the different characteristics of the roads related to the SAR and surface interaction, and secondly for the contrast within their surroundings (forest, bare soil, agricultural fields, houses, etc.). As examples, the highways are easier to locate since they are imaged over more than two to three pixels, and the houses in the city act as dihedral corner reflectors, which better define the roads when compared to less contrast for roads in the country.

IVc *DEM extraction results*: Table 2 gives the general results (LE90, bias, minimum/maximum errors) for the DEMs extracted from nine different stereoscopic pairs. By comparing the results for low and moderate relief, the relief is the important parameter that has an impact on the DEM accuracy. However, large radiometric disparities in the stereo pair depending on different criteria related to SAR and surface interaction (moisture, roughness, vegetation, foreshortening, etc.) should account for the DEM accuracy. In fact, only the radiometric issue is involved in the automatic image matching, the geometric advantage of a large VPR stereo pair cannot then compensate for the radiometric disadvantage during the matching.

As examples, in S4-H3 and S7-H6 stereo pairs comparisons the H3 and H6 images display more radiometric variations since the vegetation component tends to dominate the return signal and, in addition, the H6 (12 January 1997) low signal returns from the frozen agricultural fields. In the same way, S2-S7 stereo pair displays foreshortening for S2 and not for S7 in the moderate relief.

Table 2: Error results of the automatic image matching DEM. Stereo pairs in italic are opposite-side.

Stereo Pair	Vertical Parallax Ratio	Type of Relief	LE90 90% Confidence	Bias	Minimum Value	Maximum Value
F5-F1 Same side	0.31	***Low***	***12 m***	***-13.3 m***	***-33.2 m***	***8.4 m***
		Moderate	*36 m*	*4.2 m*	*-39.6 m*	*95.0 m*
		Entire DEM	25 m	-1.1 m	-89.1 m	95.0 m
S7-H6 Same side	0.31	***Low***	***44 m***	***-18.9 m***	***-89.4 m***	***57.5 m***
		Moderate	*58 m*	*-77.1 m*	*-153.4 m*	*-3.0 m*
		Entire DEM	85 m	-55.9 m	-270.0 m	142.1 m
S4-S7 Same side	0.39	***Low***	***24 m***	***25.8 m***	***-16.1 m***	***58.6 m***
		Moderate	*46 m*	*-6.5 m*	*-81.2 m*	*42.6 m*
		Entire DEM	45 m	-1.3 m	-126.0 m	150.3 m
S4-H3 Same side	0.59	***Low***	***23 m***	***11.7 m***	***-101.7 m***	***42.0 m***
		Moderate	*59 m*	*-18.0 m*	*-116.6 m*	*42.0 m*
		Entire DEM	54 m	-21.9 m	-161.8 m	82.0 m
S1-S4 Same side	0.97	***Low***	***15 m***	***-17.1 m***	***-40.2 m***	***16.2 m***
		Moderate	*29 m*	*10.9 m*	*-23.0 m*	*66.6 m*
		Entire DEM	23 m	-11.9 m	-81.0 m	82.0 m
S2-S7 Same side	0.99	***Low***	***16 m***	***-19.3 m***	***-44.2 m***	***13.0 m***
		Moderate	43 m	-2.0 m	-64.7 m	61.0 m
		Entire DEM	39 m	--33.9 m	-148.7 m	61.0 m
S1-S7 Same side	1.37	***Low***	***11 m***	***-3.7 m***	***-22.0 m***	***25.3 m***
		Moderate	*27 m*	*6.6 m*	*-32.0 m*	*65.6 m*
		Entire DEM	14 m	-5.0 m	-61.0 m	71.3 m
F4-F5 Opposite side	*1.97*	***Low***	***16 m***	***-15.0 m***	***-108.6 m***	***19.1 m***
		Moderate	*107 m*	*-7.4 m*	*-179.0 m*	*199.0 m*
		Entire DEM	34 m	-11.8 m	-312.7 m	199.0 m
F4-F5 Opp. side Filtered	*1.97*	***Low***	***21 m***	***-17.4 m***	***-52.4 m***	***36.8 m***
		Moderate	*77 m*	*-2.2 m*	*-132.2 m*	*132.8 m*
		Entire DEM	47 m	-14.3 m	-289.5 m	260.1 m

Conversely, the “equivalent” radiometric relief-induced disparities for S1-S7 did not adversely affect the image matching in the entire DEM. To date no valid reason has been found to explain the high percentage of good match points. One potential reason could be the close acquisition dates (24 and 22 October 1996) which have reduced the radiometric disparities due to SAR and surface interaction (such as vegetation and soil properties). Furthermore, the stronger geometry should not be the only parameter to explain these best results (LE90, bias and min/max values) since the entire DEM LE90 error decrease (64%) between S2-S7 and S1-S7 is much higher than their VPR increase (38%). More examples with other acquisition dates could resolve this ambiguity.

The opposite-side stereo pair F4-F5 gives equivalent results (16 m), only for low relief due to few radiometric disparities. Larger radiometric disparities for moderate relief cancel out its geometric advantages (VPR = 1.97). An adaptive speckle filtering (Lopes *et al.*, 1985), by slightly reducing the image contrast, smoothes the low relief to decrease the accuracy (21 m versus 16 m), but reduces the larger radiometric disparities in the moderate relief to improve the results (77 m versus 107 m).

However, two trends can be detected from the results for the three test areas (low, moderate and entire DEM):

1. With equivalent geometric disparities (same vertical parallax ratio) the best radiometric stereo pair gives better results (F5-F1 versus S7-H6; S1-S4 versus S2-S7; F4-F5 filtered versus F4-F5 in the moderate relief);
2. With equivalent radiometric disparities, the best stereo geometry gives better results (S1-S4 versus S4-S7; S1-S7 versus S2-S7; etc.).

These statements confirm that the theoretical error propagation modeling is not a good indicator by itself for predicting radargrammetric DEM accuracy since it is only computed from the SAR geometric aspects. It should be combined with the VPR and the radiometric characteristics and disparities of the stereo pair taking into account the different criteria of the SAR signal return.

V CONCLUSIONS

Previous research studies have shown a contradiction between the theoretical error propagation modeling and practical experiments, mainly in high relief. The error modeling accounts only for SAR geometric aspects, and not for radiometric ones. To resolve this contradiction, various RADARSAT stereo configurations of the Sherbrooke, Canada study site were evaluated. After the stereo model set-up, planimetric and altimetric features were extracted and directly compared with digital topographic maps and an accurate topographic derived DEM, respectively.

Previous experiments with the same data set showed that GCPs selection with stereoscopic plotting increases the stereo model set-up accuracy. It was confirmed in this experiment that the monoscopic GCP plotting error propagates through the entire processing steps to the DEM. 20% to 40% improvements on the DEM accuracy can be expected with GCP stereo plotting.

The roads were set into four categories: highways, main, secondary and city. The extraction from the F1-F5 stereo pair gave accuracy (68%) of about one resolution cell. The characteristics of each road category (width, contrast, etc.) related to SAR and surface interaction account for the small difference in accuracy. To achieve the same accuracy with roads extracted from an F1 ortho-image the DEM used in the ortho-rectification process should have an accuracy of better than 5 m.

Conversely, the 25-m accuracy DEM generated from the F1-F5 stereo pair will create an error of 30-35 m on the F1 ortho-image and any extracted feature, a four-fold degradation relative to the results achieved directly with stereo restitution from the raw SAR images.

The automatic image matching showed good results in general, less than two-resolution cell error with 90% of confidence. In flat relief, it is improved up to one resolution cell. When the radiometric disparities were too large due to relief induced distortions (S2-S7, F4-F5) or to SAR surface interaction (S4-H3, S7-H6), the results are worse. The geometric advantage (not involved in the automatic matching) due to a stronger geometry cannot compensate for its radiometric disadvantage. Surprisingly, the largest radiometric disparities in S1-S7 did not disturb the matching, and consequently achieve the best results with a stronger geometry.

Since the relief is an important parameter in the final accuracy, Table 3 gives geometric versus radiometric disparity tradeoffs and general guidelines for selecting RADARSAT stereo pairs for DEM generation. They have to be weighted as a function of the radiometric characteristics and disparities of the stereo pair taking into account the SAR and surface interaction (surface geometry, vegetation, soil properties, geographic conditions, etc.).

Table 3: Geometric versus radiometric disparity tradeoffs and general guidelines for selecting RADARSAT stereo pairs for DEM generation as a function of terrain relief.

Terrain Relief Slopes	Flat 0° - 10°	Rolling 10° - 30°	Mountainous 30° - 50°
Radiometric Disparities	Small	Medium	Large
Geometric Disparities	Large	Medium	Small
Compromises	Opposite-side with steep look angles	Same-side with large intersection angle *or* (Opposite-side with shallow look angles)	Same-side with small intersection angle and shallow (or steep) look angles
Stereo RADARSAT Configurations	S1desc-S1asc F1desc-F1asc	S1-S7 (desc or asc) F1-F5 (desc or asc) *or* S7 desc-S7 asc F5 desc-F5 asc	S1-S4 (desc or asc) F2-F5 (desc or asc) S4-S7 (desc or asc) F1-F4 (desc or asc)

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