GEOMETRIC ASPECTS OF SPACEBORNE STEREO IMAGING RADAR

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ABSTRACT

RADARSAT, a Canadian spaceborne imaging radar system is scheduled for launch by the end of this decade. The interpretation of such images will be enhanced by stereoscopic capability, permitting the determination of terrain elevations and slopes. With particular reference to the proposed RADARSAT, the geometric aspects of satellite stereo radar are addressed. The vertical exaggeration factor is used as a measure of stereo viewability for various geometric configurations. A theoretical accuracy analysis of the height determination process is presented. Visual assessment of, and measurement in models formed with simulated images are employed to substantiate the findings of the theoretical investigation.

INTRODUCTION

The all-weather, solar-independent imaging potential of synthetic aperture radar (SAR) has prompted Canada to support the development of RADARSAT, a polar-orbiting satellite-borne SAR sensor due for launch in 1990. With increasing exploration and economic activity in the far north, off-shore and elsewhere, the RADARSAT would provide much needed information for navigation, geological exploration and resource management.

The proposed baseline altitude of the satellite is 1000 km and the operational range of the sensor, over which imagery may be obtained, is limited to a region bounded by incidence angles 20° and 45° (Figure 1). An increase in the maximum incidence angle to 50° may be possible.

The sensor cannot cover the entire operational range in one swath. Therefore, four subswaths were selected where imaging is possible by switching the antenna to the appropriate look angle. The incidence angles which bound each subswath and the width of the swaths in ground range are (Figure 1):

Swath 1	20.00° to 33.77°	250 km
Swath 2	27.61° to 38.13°	209 km
Swath 3	33.16° to 41.81°	187 km
Swath 4	37.62° to 45.00°	172 km

[RADARSAT, 1982].

In anticipation of a possible increase of the incidence angle to 50°, a fifth subswath was included in the investigation. The incidence angles and the width of this hypothetical subswath are:

Swath 5	43.50° to 50.00°	67 km

It is a well known fact that stereoscopy considerably enhances the visual interpretability of images and is a necessary requirement for the determination of the third dimension. Therefore, stereo data acquisition capability is part of the design parameters of RADARSAT.

Stereo radar is a complex problem and has been the subject of several studies since 1963 [La Prade, 1963, 1970; Rosenfield, 1968; Leberl, 1979; Leberl et al., 1982]. The investigation reported in this paper was conducted with reference to RADARSAT.

RADAR STEREOSCOPY

Radar images of the same area, acquired from adjacent passes form stereo pairs. Relief displacement on SAR images is perpendicular to the velocity vector of the sensor and is inversely proportional to the incidence angle of the impinging radiation. A general concensus has yet to be reached, however, regarding the optional configurations of the radar when collecting imagery for stereoscopic analysis.

The strength of depth perception in any stereo model, radar included, is a function of the vertical exaggeration which is present. Vertical exaggeration, q, is defined as:

$$q = \frac{\text{perceived height to base ratio in stereomodel}}{\text{height to base ratio of actual object}} .$$

La Prade [1980] has ascertained that q can be quantified as

$$q = 5dp / h , \qquad (1)$$

where dp is the parallax difference and h the height of the object. Since for radar

$$dp = h (\cot \alpha_2 - \cot \alpha_1) , \qquad (2)$$

where α_1 and α_2 are the two incidence angles, q becomes

$$q = 5 (\cot \alpha_2 - \cot \alpha_1) . \qquad (3)$$

Vertical exaggeration across a radar overlap is therefore not constant as it is in a perspective stereo model. Instead, q decreases nonlinearly from near to far range. From tables of functions, it can be seen that the intersection angle $(\alpha_1 - \alpha_2)$ is not necessarily the indicator of the magnitude of q. For example, the configuration consisting of images with incidence angles 25° and 20° produces parallax differences of an equivalent magnitude to those of a configuration with 50° and 35°.

Hence, when evaluating the utility of a stereo configuration, intersection angle is not the only consideration. Instead, a more realistic evaluation is obtained by considering the parallax differences, expressed in terms of q, which will be present, since these parallax differences govern the appearance of the third dimension in the model. It can be seen that the geometry of the radar stereo model is such that large parallax differences can occur even when the intersection angle is small. Large differences in parallax, of course, render enhanced perception of elevation in the model.

STEREO VIEWABILITY OF RADARSAT CONFIGURATIONS

"Stereo viewability" is a term which is difficult to define precisely but which is considered to be an indication of the visual quality of a stereo model and of its utility to facilitate image analysis [Derenyi and Stuart, 1983]. It is, therefore, a function of both image quality and stereo geometry and the vertical exaggeration factor, q, is a useful indicator.

The vertical exaggeration factor for conventional aerial photography is given by:

$$q = 5B / H , \tag{4}$$

where B is the air base and H is the flying height.

The value of q generally varies between approximately 3 (wide angle lens, f = 152 mm) and 5 (super-wide angle lens, f = 88 mm) with a 60% forward overlap. These values provide a yardstick by which q for radar configurations may be assessed. The interval 3 to 5 does not, however, define exclusive bounds on the useful values of the parameter q.

The magnitude of variation of q across an overlap is another factor in assessing radar stereo viewability. It is expressed by the ratio

$$dq = q_n / q_f , \tag{5}$$

where q_n and q_f are the vertical exaggeration factors at the near- and far-range edges of the overlap respectively. For good stereo perception dq should be close to one.

Using a 60% sidelap, several configurations are identified as being the most promising of the many possible. Details of these configurations are given in Table 1. Of these arrangements, the combination of subswath 5 and 2 offers perhaps the best overall characteristics. In the event that power requirements restrict the maximum incidence angle to 45^{o}, then a 60% sidelap of subswath 2 by subswath 4 and of subswath 1 by 4, 3 and, possibly, 2 are configurations which appear to possess the most desirable properties of stereo viewability.

The best way of gaining more idea of the useful range of q and the problem concerning dq is by the examination of a series of stereo pairs in a stereoscopic viewing device. Unfortunately, stereo radar imagery acquired from earth-orbiting satellites is practically non-existant. Therefore, the investigation was conducted using simulated images.

Four sets of computer-generated simulations were obtained from the University of Arkansas [Kaupp et. al., 1982]. The input to the simulation program consisted of digital elevation data

Table 1: Most Promising RADARSAT Stereo Configurations.

Subswath Pairs	$\Delta\alpha^{o}$ near-far	q near-far	dq
5 / 2	15.8 - 17.8	3.2 - 4.6	1.46
4 / 2	10.9 - 12.1	2.4 - 3.6	1.50
4 / 1	16.4 - 18.6	4.2 - 7.5	1.79
3 / 1	13.2 - 15.0	3.6 - 6.6	1.84
5 / 3	11.5 - 12.7	2.1 - 2.8	1.35
2 / 1	9.6 - 10.8	2.8 - 5.3	1.90

derived from USGS 1:24 000 scale topographic maps. A SAR with 30 m spatial resolution (in range and azimuth), orbiting at 800 km altitude above sea level was assumed.

The model areas are representative of three broad categories of terrain: low, moderate and high relief. All image areas cover 13.86 km on the ground in the range direction. The images are in ground-range presentation. The effect of noise or speckle has not been incorporated in the simulation algorithm. The simulated antennae and flight path are parallel. Hence the images are in a form which makes for optimal stereo viewing without many of the disturbing factors which would be present in a real system. Incidence angle is the only variable parameter, hence the images differ only in the size of the relief displacements present. For the purposes of these initial investigations, however, the images are probably sufficiently realistic to enable broad conclusions to be drawn.

Of each site, images were produced with eleven angles of incidence. Of these, only five are relevant to RADARSAT, namely 23^{o}, 30^{o}, 35^{o}, 40^{o} and 50^{o} and were used for visual appraisals. Positive paper prints, made at a scale of 1:100,000 from the original 35 mm negatives, were used for the tests by two independent observers.

VISUAL APPRAISAL OF STEREO PAIRS

Stereo perception was possible with every configuration used. In areas of high relief, however, a large q prevented simultaneous fusion of all elevations. The model formed by incidence angles of 50^{o} and 23^{o} for the high relief area, for example, has a value for q of around 7.6. The observers found it possible to fuse either the top or the base of a mountain but not both at the same time. Viewing of significantly different elevations required adjustment of the convergence angle of the eyes or the relative positions of the images. For this mountainous region, the preferred stereo configurations had relatively small values for q. Angles 40^{o} / 30^{o} (q = 2.70) and 50^{o} / 40^{o} (q = 1.76) were both considered to be comfortable for viewing within the entire range of elevations.

The preferred configurations in regions of lower relief exhibited larger vertical exaggeration factors such that topographic details are well defined. Hence, 60^{o} / 23^{o} and

50^o / 23^o, which were unfavourable for high relief, were considered to produce excellent stereo models. Some configurations with smaller intersection angles were, however, adjudged to yield satisfactory stereo. Intersection angles of less than 10^o were considered almost useless for this low relief. Configuration 40^o / 23^o generates quite creditable stereo (q = 5.82) and a very workable model. 50^o / 35^o, while having a much smaller q (only = 2.94) was still capable of rendering perception of minor undulations in the low-lying plains and valleys. Similarly, 40^o / 30^o was quite satisfactory despite a vertical exaggeration factor of only 2.70. Five degree intersection angles (40^o / 35^o, 35^o / 30^o) are of no appreciable value for stereo viewing in areas of low relief. Most configurations gave rise to at least a reasonable stereo impression in the moderate relief model area. Even unfavourable arrangements such as 35^o / 30^o (q = 1.52) and 40^o / 35^o (q = 1.18) would be workable. For the sake of comparison, the observers were presented with a pair of images with incidence angles of 70^o and 65^o. As expected, the stereo impression was very poor (q = 0.51) and the configuration was considered to be completely useless.

In low and moderate relief, the most favourable arrangements were those which employed the smallest incidence angle in combination with a much larger incidence angle. This results in a large vertical exaggeration and enhanced perception of minor relief. For more extreme topography, very small incidence angles result in layover while very large angles produce radar shadow. The best stereo configurations then are those with the smaller incidence angle at 30^o or 40^o and the larger incidence angle at around 50^o. In the context of proposed satellite parameters and on the basis of these stereo observations, the configurations judged as being optimal for stereo viewing are:

Low Relief:	$\alpha_1 = 40^o - 50^o$	$\alpha_2 = 20^o - 30^o$
Moderate Relief:	$\alpha_1 = 40^o - 50^o$	$\alpha_2 = 20^o - 30^o$
High Relief:	$\alpha_1 = 45^o - 50^o$	$\alpha_2 = 30^o - 40^o$

Good agreement exists between these results and the optimal configurations from the numerical considerations, presented in Table 1. Reconciling the two sets of results provides the following recommendations for stereo viewing of RADARSAT imagery.

For low relief, a combination of subswath 5 (if available) or 4 with 1 seems to be most suitable. In areas of moderate relief, less extreme vertical exaggeration is necessary. Hence, an arrangement of subswath 5 or 4 with 2 or 1 would provide workable stereo. To minimise layover, subswath 2 or 3, but not 1, can be employed in mountainous terrain. To maintain adequate intersection angles, the largest available incidence angle should be used as the stereo partner.

HEIGHT DETERMINATION

Rigorous stereo radar space intersection has been formulated by several researchers including Rosenfield (1968) and Leberl (1975b). These rigorous approaches are, by necessity, computationally involved and require precise records of the dynamic variables of sensor position and orientation. This investigation was concerned with a much simpler, faster and cheaper approach. Widespread use of stereo radar imagery by interpreters requires that reliable terrain height information can be derived using relatively simple equipment.

THEORETICAL ACCURACY OF HEIGHT DETERMINATION

The planetary surface is assumed to be locally approximated by a plane and the flight lines to be rectilinear and parallel. The equation relating height difference to parallax difference is:

$$dh = [dp(\cot \alpha_2 - \cot \alpha_1)]S \ , \qquad (6)$$

where S is the image scale.

Parallax difference is determined as the algebraic difference between two independent measurements of parallaxes. That is,

$$dp = p_t - p_b \ , \qquad (7)$$

where p_t and p_b are the parallax measurements at the top and bottom of the object respectively. The measurement error is then:

$$\sigma dp = (\sigma p_t^2 + \sigma p_b^2)^{1/2} \ , \qquad (8)$$

where σp_t usually equals σp_b, hence;

$$\sigma dp = \sqrt{2} \ \sigma p \ .$$

Therefore, the error in the height difference (at the 68% confidence level) can be ascertained as:

$$\sigma dh = [\sqrt{2} \ \sigma p \ / \ (\cot \alpha_2 - \cot \alpha_1)]S \ . \qquad (9)$$

In the context of digital images, it is of value to express errors and accuracies in terms of pixels rather than absolute units on the ground. In this way, accuracies are easily computed for any particular image scale by simply inserting the appropriate pixel ground dimensions. In any parametric trade-off analysis, it is necessary to find the effect of variations in one parameter while holding others constant. It is also useful to graphically plot the variations. For this purpose, the equation for height differences can be reduced to three variables by letting S = 1 and introducing the vertical exaggeration factor:

$$q = 5(\cot \alpha_2 - \cot \alpha_1) \ .$$

Substituting into (9):

$$\sigma dh = (5\sqrt{2}\,\sigma p / q)\ . \qquad (10)$$

Hence, height difference error, σdh, is inversely proportional to vertical exaggeration.

From Figure 2, it is apparent that σdh decreases at an exponentional rate with increasing vertical exaggeration. Furthermore, from the figure, if individual parallax measurements can be made with a precision of, $\sigma p = \pm 0.5$ pixel (i.e., $\sigma dp = \pm 0.7$ pixel) then, in configurations with $q > 3.5$, height difference errors will be less than ± 1 pixel at the 68% confidence level. If, however, $\sigma p = \pm 1.0$ pixel (i.e., $\sigma dp = \pm 1.4$ pixel) then $\sigma dh = \pm 1$ pixel only when $q \geq 7$.

In stereo pairs of aerial photographs, a constant parallax difference defines the separation between two planes, parallel to the model datum. Equation (6) shows that height differences in radar stereo models are dependent not only upon parallax differences but also upon the incidence angles.

Substituting $q / 5$ for $(\cot \alpha_2 - \cot \alpha_1)$ in (6.1):

$$dh = (5\ dp / q)S\ . \qquad (11)$$

The extent of the variation of q with range across a stereo overlap was demonstrated previously. Correspondingly, for a constant elevation difference, dh, between two horizontal planes A and B, parallax differences in a radar stereo model is not constant but decreases non-linearly with increasing range.

EXPERIMENTAL RESULTS

Measurements were made on the simulated images in a Jena 1818 stereocomparator with an 8x magnification. Film diapositives at a scale of 1:750,000 were used. Observations were performed twice, in forward and backward series, and the standard errors, $\sigma\Delta$, for the unbiased differences determined. Each coordinate and parallax difference was compared with $2\sigma\Delta$ and those found to lie outside the 95% confidence interval were rejected as blunders. The standard error of the parallax measurements was of the order of 10 µm. At the scale of 1:750,000, 10 µm represents one-quarter of the nominal image resolution of 30 m at object scale. The precision of 10 micrometres approaches and instrumental limit and may not represent the best obtainable with the imagery. A series of 16 points along a profile line was measured in each model formed with the test images. Height differences with respect to an arbitrary point, approximately midway along the profile were computed and the RMSE derived (Table 2).

Representative results of crude height computations based on the parallax measurements are also presented in Table 2. The accuracy of crude height determination is approximately equivalent to that of height differences because of the idealised geometry.

Table 2: Height Difference Errors.

Model	q	RMSE (m) of profile points	RMSE (m) of crude heights
50^{o} / 23^{o}	7.6	6.4	12.8
40^{o} / 23^{o}	5.8	6.2	10.2
50^{o} / 30^{o}	4.5	8.0	10.8
30^{o} / 23^{o}	3.1	11.8	18.0

The accuracy of the profile height differences is superior to the theoretical accuracy for a measurement precision, σp of 10 µm and the accuracy of crude heights also approaches the theoretical values. Plotting the RMSE for the 15 non-datum profile points and the 76 check points against vertical exaggeration of the stereo configurations measured, the trend follows closely the theoretical accuracy curve (Figure 3), although for q greater than approximately 6, the predicted accuracy increase was not realised. Despite this, Equation (10) would appear to be validated.

CONCLUSIONS

Stereo viewability of a radar stereo model and the accuracy of height determination are affected by the vertical exaggeration factor. This in turn is governed by the cotangent of the two incidence angles and is not constant, as in aerial photographs, but decreases across the swath from near- to far-range. There is no direct relationship between the size of stereo intersection angle and vertical exaggeration.

It is expected that the proposed RADARSAT will provide imagery useful for stereo viewing. A judicious selection of subswath configurations will, however, be necessary to assure good stereo perception and to attain optimal height measuring accuracy.

The theoretical investigation and the measurements made on simulated imagery indicate that determination of height differences is possible with sub-pixel accuracy. However, theoretical accuracies are likely to be degraded by system noise and perturbations of the image-collection geometry. Therefore, the results presented here should be utilized for the evaluation of the geometric strength of the various RADARSAT stereo configurations in a relative sense, rather than as an absolute measure of accuracy.

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REFERENCES

Derenyi, E.E. and A.J. Stuart (1983), "Stereo Viewability of Proposed Radarsat Imagery", Proceedings of the 8th Canadian Symposium on Remote Sensing, Montreal, May 3-6.

Kaupp, V.H., L.C. Bridges, M.A. Pisaruck, H.C. MacDonald and W.P. Waite (1982), "Comparison of Simulated Stereo Radar Imagery", Proceedings of the International Geoscience and Remote Sensing Symposium, Munich, June 1-4.

LaPrade, G.L. (1963), "An Analytical and Experimental Study of Stereo Radar", Photogrammetric Engineering, Vol. 29, No. 2, pp. 294-300.

LaPrade, G.L. (1970), Subjective Considerations for Stereo Radar, Goodyear Aerospace Publication GIB-9169.

LaPrade, G.L. (1980), Chapter 10, "Stereoscopy", Manual of Photogrammetry, Fourth Edition, American Society of Photogrammetry, Washington, D.C.

Leberl, F. (1979). Accuracy Aspects of Stereo Side-Looking Radar, JPL Publication 79-17, NASA JPL, California Institute of Technology, Pasedena, California.

Leberl, F., J. Raggam and M. Kobrick (1982), "Stereo Side-Looking Radar Experiments", Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS), Munich, June 1-4.

RADARSAT Project Office (1982), RADARSAT Mission Requirements Document, Energy, Mines and Resources, Canada, Ottawa.

Rosenfield, G.H. (1968). "Stereo Radar Techniques", Photogrammetric Engineering, Vol. 34, No. 6, pp. 586-594.

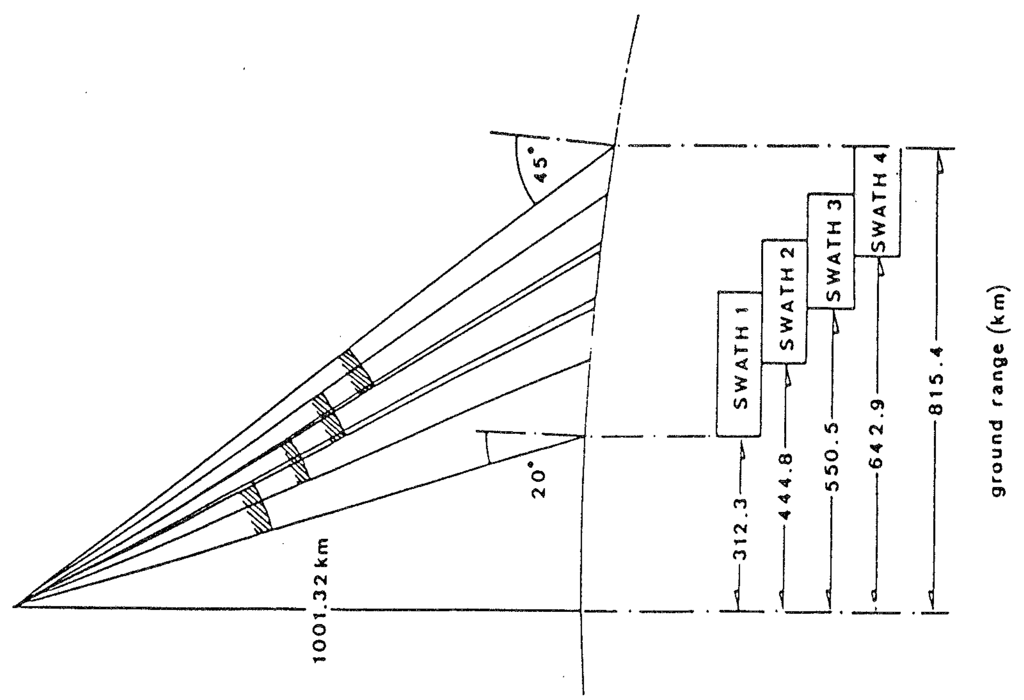

Figure 1: RADARSAT ground coverage

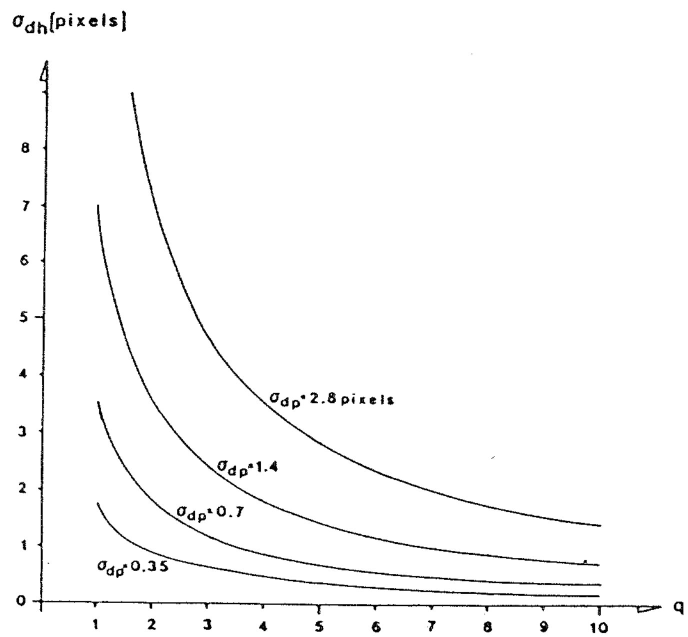

Figure 2: Height difference error as a function of vertical exaggeration for measurement errors, σ_p = 0.25, 0.5, 1.0 and 2.0 pixels

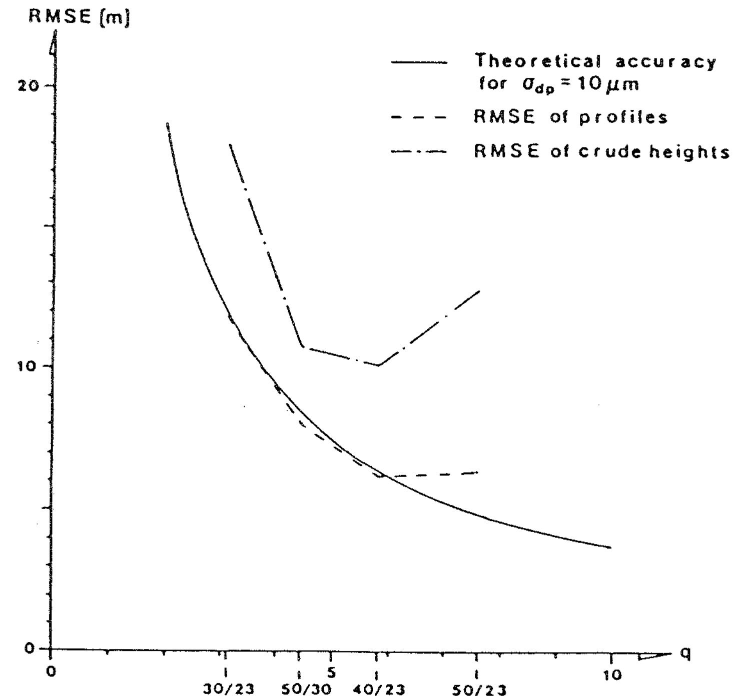

Figure 3: Profile and crude height errors