RADARSAT FOR STEREOSCOPY[*]
THE QUEST FOR RADAR STEREO PAIRS FOR DEM GENERATION

Stereo SAR research uncovered contradictions and a dichotomy between error propagation theory and practical results. Now, RADARSAT enables us to resolve it, and to define general guidelines for selecting RADARSAT stereo pairs for DEM generation.

By Thierry TOUTIN

Leader: *In the 1960's, stereoscopic methods were first applied to radar images to derive ground elevation. Unfortunately, research uncovered contradictions and a dichotomy between error propagation theory and practical results, particularly over high relief areas. This dichotomy combined with the lack of stereo radar pairs led to the decline of radargrammetry. The launch in 1995 of Canada's first earth observation satellite, RADARSAT with its various operating modes and specific geometric characteristics has turned the tide. We are now able to understand and resolve this dichotomy, and to define general guidelines for selecting RADARSAT stereo pairs for DEM generation as a function of terrain relief.*

Digital Elevation Model (DEM) generation from stereo Synthetic Aperture Radar (SAR) images has once more become a hot R&D topic. However, stereoscopy using SAR data is more problematic than VIR stereoscopy, which emulates human stereo vision. An *a priori* understanding of the physical components of stereo SAR is a pre-requisite for any processing and product generation.

WHAT IS THE STEREO SAR DICHOTOMY?

To obtain good stereo geometry for better plotting, the intersection angle[1] should be large in order to increase the stereo exaggeration factor or, equivalently, the observed parallax, which is used to determine the terrain elevation (Figure 1). Conversely, optimum stereo viewing or matching requires a stereo pair as nearly identical as possible - this in turn implies a small intersection angle.

Numerous research studies have assessed stereo-capabilities of radar for DEM generation: first with simulated data, due to the lack of a wide range of radar data to generate different stereo-configurations, and then with operational (SIR, ERS, JERS and airborne) data. The more interesting results to date can be summarized as follows:

1. the optimum intersection angles were found to be about 40°- 45°;
2. the best subjective impressions were obtained with shallow look angles (50-70°), and at an intersection angle of 20°;
3. the highest accuracy is not necessarily achieved with the largest intersection angles;

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[1] The intersection angle is the difference between the two incidence angles.

4. higher ground resolution does not necessarily lead to higher height accuracy; and
5. better results are more consistently achieved with opposite-side stereo viewing.

WHAT ARE THE CONSEQUENCES OF THIS DICHOTOMY?

Practical experiments are sometimes inconsistent and do not clearly support theoretical expectations. For example, larger intersection angles and higher spatial resolution do not translate into higher accuracy. In various experiments, accuracy trends even reverse, especially for rough topography. Only in the extreme case of low relief, does accuracy approach theoretical expectations.

Theoretical error propagation modeling has a major limitation since it accounts only for the geometric aspects and completely neglects the radiometric aspects of the stereo pair. It is well known that the SAR backscatter –and consequently the image radiometry- is much more sensitive to the incidence angle than the VIR reflectance, especially at low incidence angles. Care must therefore be taken in attempting to apply VIR stereo concepts to SAR.

HOW TO RESOLVE THIS DICHOTOMY?

Large geometric and radiometric disparities both hinder stereo viewing and precise stereo plotting. Since the reduction of one disparity could compensate for the other disparity, a tradeoff (steep or shallow look angles, small or large intersection angle, fine or coarse resolution) has to be reached between better stereo viewing (small radiometric differences) and stronger stereo geometry and plotting (large parallax) (Figure 1).

In general, the tradeoff for any type of relief is to use a same-side stereo-pair, thus reducing both disparities. Unfortunately, this does not maximize the full potential of stereo radar for all topography. The tradeoff between minimizing the radiometric disparities and maximizing the geometric disparities must take into account not only the terrain and its relief, but also the thematic application and its objectives, such as the image content, the type and level of information to be extracted, and the preferred DEM characteristics.

HOW CAN RADARSAT HELP?

Historically, the assessment of different radar stereo viewing strategies was impeded by a lack of suitable stereo data sets. Before RADARSAT, no satellite, and few airborne radar systems provided data over a broad range of viewing geometry for which this tradeoff could be quantitatively analyzed. RADARSAT (Figure 2), which acquires imagery from a broad range of look directions (ascending, descending), beam positions (steep, shallow) and modes (fine, standard, wide, scanSAR) at different resolutions (one or four looks) meets this need.

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

To date, twelve RADARSAT images of the Sherbrooke region, Quebec, have been studied in detail. The relief of the region is moderate with a 350-m elevation range and up-to-30° slopes (Figure 3). The image data set includes:

1. Four fine mode scenes, 6.25-m pixel spacing, ascending orbit (F1 and F5) and descending orbit (F2 and F4); and
2. Eight standard or extended mode scenes, 12.5-m pixel spacing, descending orbit (S1, S4, S7, EH3 and EH6) and ascending orbit (S2, S5 and S7).

Two methods for the DEM extraction from nine different RADARSAT stereoscopic pairs were assessed using a CCRS developed geometric correction system:

1. A computer-assisted visual matching on a PC-based softcopy stereo workstation, the DVP, to verify the impact of the geometric disparities; and
2. An automatic image matching on a digital image analysis system, PCI, to verify the impact of the radiometric disparities.

The extracted DEMs were then directly compared with a 5-m accurate DEM derived from 10-m contour lines of 1:50,000 maps.

COMPUTER-ASSISTED VISUAL MATCHING DEM

Table 1 summarizes accuracy of DEMs extracted from nine different stereoscopic pairs on different types of relief. Only the last two are opposite-side pairs (89°-intersection angle) created from ascending (asc.) and descending (desc.) orbits. In addition, the last one was also radiometrically pre-processed with an adaptive speckle filtering to reduce the radiometric disparities.

Why is the type of relief the only parameter that has a significant impact on the precision of the DEM? The key results are summarized below:

1. There is no correlation between the intersection angles and the LE90 results for the low or moderate relief sites: the greater the variation between two look angles (S1-S7) when compared to S1-S4 or S4-S7, the more the quality of the stereoscopic fusion deteriorated. This cancels out the advantage obtained from the better stereo viewing geometry.
2. The opposite-side stereo pair F4-F5 gives better results only for low relief (few radiometric disparities). Larger radiometric disparities for moderate relief, which was also reduced with the speckle filtering, cancel out its geometric advantages;

3. Steep stereo pair S1-S4 with a larger vertical parallax ratio than shallow stereo pairs S4-S7 or S7-H6 with better radiometry does not provide significantly better results;
4. Although a higher resolution (F1-F5) produced a better quality stereo pair when compared to S4-S7, it did not change the precision of the stereoscopic plotting for a given configuration (8°-10°-intersection angle). Furthermore, although the speckle does not degrade the stereoscopic viewing, it does create some confusion in the stereo plotting.

AUTOMATIC IMAGE MATCHING DEM

Since automatic image matching is more sensitive than visual matching to radiometric disparities, the relief is no longer the only parameter that has an impact on the DEM accuracy. Two trends can be detected from the results for areas of low and moderate relief (Table 2):

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.).

For the opposite-side stereo pair, the same explanation as before applied: only the moderate relief results are improved with the speckle filtering.

Understanding the results for the entire DEM is more challenging because they comprise different percentages of low and moderate relief due to different overlaps between the stereo pairs and the accurate reference DEM. Stereo pairs S4-H3 and S2-S7 have more moderate relief than S1-S7, which explains the worse results. Since the relief is never homogeneous, a single DEM error value on a large area is not sufficient. To better describe your DEM accuracy, different values or levels of confidence should be ascribed that correspond to different terrain relief.

CONCLUSIONS

For wide separation of look angles, better stereo geometry is offset by poorer image fusion in the stereo viewing or matching. This implies that a tradeoff has to be reached for the reduction of either the geometric or the radiometric disparities. This tradeoff in the choice of the “better” stereo pair must take into account principally the terrain. However the images are generally not only used for DEM generation, the projected application requirements of the DEM and the thematic use of the images are thus other elements in the tradeoff.

Since the type of relief is the principal parameter that affects the accuracy of a DEM, it is strongly recommended that the DEM accuracy be ascribed values that reflect the different areas of relief. Finally, Table 3 gives geometry versus radiometry tradeoffs and general guidelines for selecting RADARSAT stereo pairs for DEM generation.

Biography of the Author

Thierry Toutin, educated both in France and Canada, received his Dr.-Ing. degree from the Ecole Nationale des Sciences Géographiques in Paris. He joined the Canada Centre for Remote Sensing in 1988 as a research scientist. He currently develops mathematical tools and pre-operational systems for the monoscopic and stereoscopic processings of a broad range of remote sensing data. His main fields of interest are cartographic applications of remote sensing data, multi-source data fusion and 3D visualization.

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Stereo pair	Beam mode	Resolution	Look angles	Intersection angle	Type of relief	LE90 90%	Bias	Minimum Values	Maximum Values
F1 asc.	Fine	9m x 8m	37° – 40°	8°	***Low***	***21m***	***-7.2m***	***-44.6m***	***42.6m***
F5 asc.	Fine	7m x 8m	45° – 48°		Moderate	39m	-5.5m	-78.5m	70.7m
S4 desc	Standard	26m x 27m	34° – 40°	10°	***Low***	***24m***	***7.8m***	***-36.4m***	***53.8m***
S7 desc.	Standard	20m x 27m	45° – 49°		Moderate	35m	1.4m	-58.8m	74.9m
S7 desc.	Standard	20m x 27m	45° – 49°	11°	***Low***	***26m***	***-1.4m***	***-49.1m***	***46.6m***
H6 desc.	Extended	17m x 27m	57° – 59°		Moderate	42m	8.6m	-78.8m	86.1m
S1 desc.	Standard	29m x 27m	20° – 27°	13°	***Low***	***20m***	***3.4m***	***-48.7m***	***51.3m***
S4 desc.	Standard	26m x 27m	34° – 40°		Moderate	37m	11.7m	-43.0m	82.2m
S4 desc.	Standard	26m x 27m	34° –40°	15°	***Low***	***23m***	***2.3m***	***-32.9m***	***45.3m***
H3 desc.	Extended	18m x27m	51° - 55°		Moderate	37m	0.4m	-69.1m	74.4m
S7 asc.	Standard	20m x 27m	45° – 49°	19°	***Low***	***21m***	***-2.4m***	***-40.5m***	***36.4m***
S2 asc.	Standard	24m x 27m	24° – 31°		Moderate	41m	6.3m	-94.5m	69.9m
S1 desc.	Standard	29m x 27m	20° – 27°	22°	***Low***	***22m***	***6.9m***	***-36.9m***	***56.9m***
S7 desc.	Standard	20m x 27m	45° – 49°		Moderate	41m	9.3m	-68.2m	88.6m
F4 desc.	*Fine*	*8m x 8m*	*43° – 46°*	*89°*	***Low***	***12m***	***-5.6m***	***-27.7m***	***21.8m***
F5 asc.	*Fine*	*7m x 8m*	*45° – 48°*		Moderate	47m	11.7m	-66.1m	109.7m
F4 filter	*Fine*	*8m x 8m*	*43° – 46°*	*89°*	***Low***	***14m***	***-7.8m***	***-30.0m***	***28.1m***
F5 filter	*Fine*	*7m X 8m*	*45° – 48°*		Moderate	44m	6.6m	-97.0m	114.3m

Stereo Pair	Beam Mode	Resolution	Look Angles	Intersection Angle	Type of Relief	LE90 90%	Bias	Minimum Values	Maximum Values
F1 asc.	Fine	9m x 8m	37° – 40°	8°	*Low*	***21m***	***-7.2m***	***-44.6m***	***42.6m***
F5 asc.	Fine	7m x 8m	45° – 48°		Moderate	39m	-5.5m	-78.5m	70.7m
S4 desc	Standard	26m x 27m	34° – 40°	10°	*Low*	***24m***	***7.8m***	***-36.4m***	***53.8m***
S7 desc.	Standard	20m x 27m	45° – 49°		Moderate	35m	1.4m	-58.8m	74.9m
S7 desc.	Standard	20m x 27m	45° – 49°	11°	*Low*	***26m***	***-1.4m***	***-49.1m***	***46.6m***
H6 desc.	Extended	17m x 27m	57° – 59°		Moderate	42m	8.6m	-78.8m	86.1m
S1 desc.	Standard	29m x 27m	20° – 27°	13°	*Low*	***20m***	***3.4m***	***-48.7m***	***51.3m***
S4 desc.	Standard	26m x 27m	34° – 40°		Moderate	37m	11.7m	-43.0m	82.2m
S4 desc.	Standard	26m x 27m	34° –40°	15°	*Low*	***23m***	***2.3m***	***-32.9m***	***45.3m***
H3 desc.	Extended	18m x27m	51° - 55°		Moderate	37m	0.4m	-69.1m	74.4m
S7 asc.	Standard	20m x 27m	45° – 49°	17°	*Low*	***21m***	***-2.4m***	***-40.5m***	***36.4m***
S2 asc.	Standard	24m x 27m	24° – 31°		Moderate	41m	6.3m	-94.5m	69.9m
S1 desc.	Standard	29m x 27m	20° – 27°	22°	*Low*	***22m***	***6.9m***	***-36.9m***	***56.9m***
S7 desc.	Standard	20m x 27m	45° – 49°		Moderate	41m	9.3m	-68.2m	88.6m
F4 desc.	*Fine*	*8m x 8m*	*43° – 46°*	*89°*	*Low*	***12m***	***-5.6m***	***-27.7m***	***21.8m***
F5 asc.	*Fine*	*7m x 8m*	*45° – 48°*		Moderate	47m	11.7m	-66.1m	109.7m
F4 filter	*Fine*	*8m x 8m*	*43° – 46°*	*89°*	*Low*	***14m***	***-7.8m***	***-30.0m***	***28.1m***
F5 filter	*Fine*	*7m X 8m*	*45° – 48°*		Moderate	44m	6.6m	-97.0m	114.3m

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***	***31 m***	***-50.4 m***	***-99.4 m***	***12.5 m***
		Moderate	*22 m*	*-57.5 m*	*-106.0 m*	*-6.0 m*
		Entire DEM	56 m	-76.3 m	-221.5 m	62.0 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

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

Table 3: Geometry versus radiometry 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)

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	Opposite-side with shallow look angles *or* Same-side with large intersection angle	Same-side with small intersection angle and steep or shallow look angles
Stereo RADARSAT Configurations	S1desc-S1asc F1desc-F1asc	S7desc-S7asc F5desc-F5asc *or* S1-S7 (desc or asc) F1-F5 (desc or asc)	S1-S4 (desc or asc) S4-S7 (desc or asc) F1-F4 (desc or asc) F2-F5 (desc or asc)

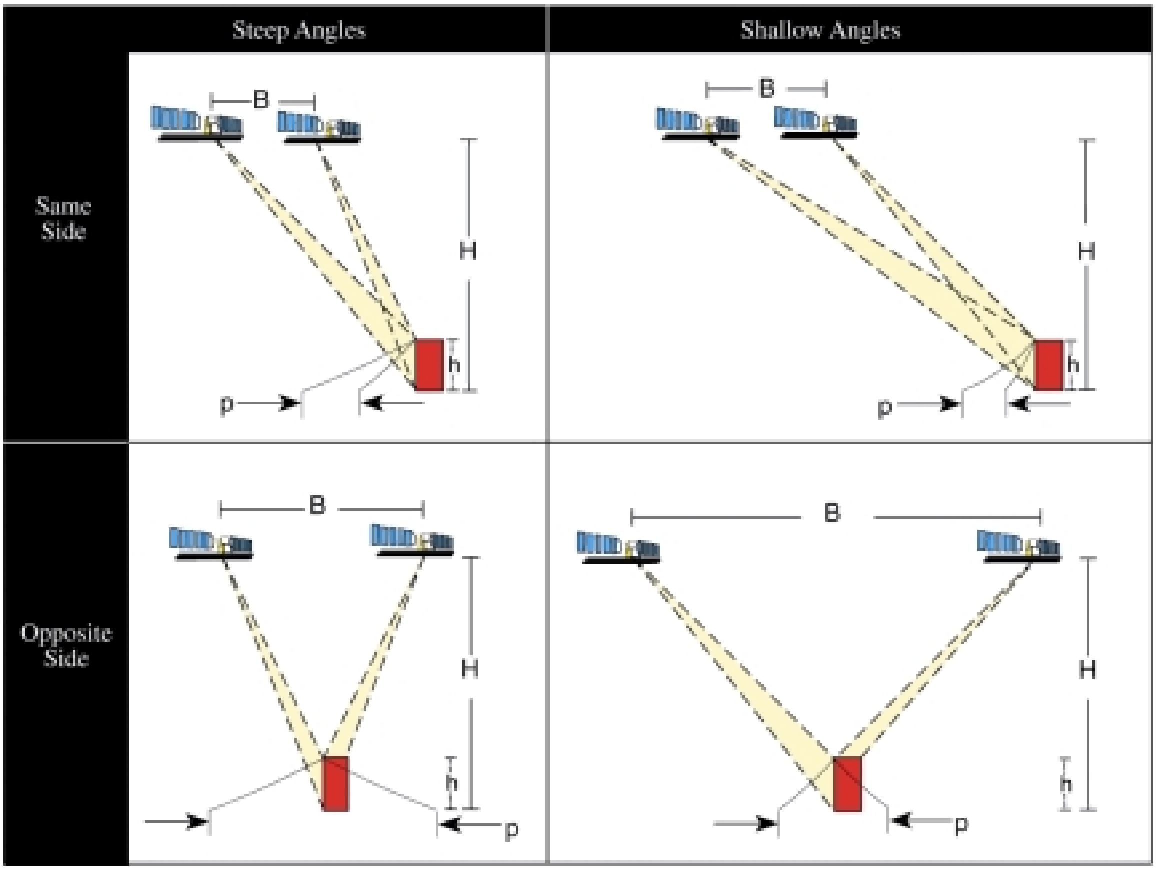

Figure 1: Various configurations of RADARSAT-SAR stereo pairs (same and opposite sides; steep and shallow angles).

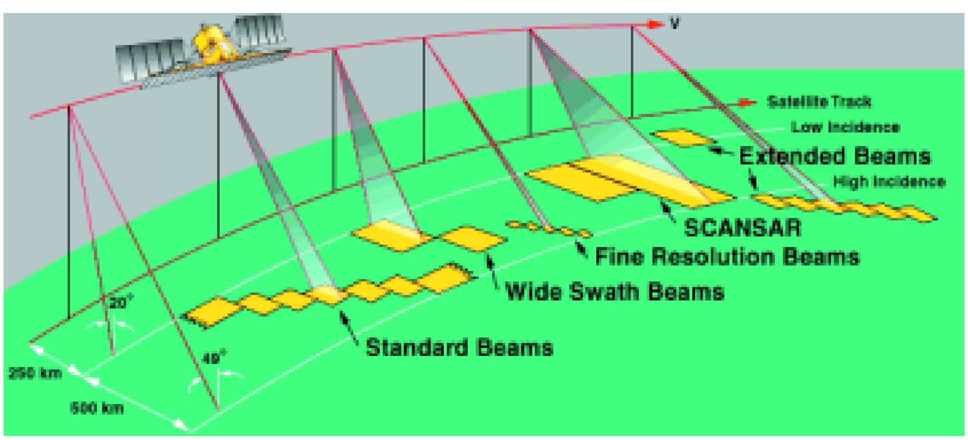

Figure 2: Operating modes of RADARSAT-SAR.