Multiple Incidence Angle SIR-B Experiment Over Argentina: Stereo-Radargrammetric Analysis

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Abstract—Four overlapping SIR-B radar images were obtained across southern Argentina; these form a total of six stereo models with intersection angles ranging from 5° to 23°. This data set is uniquely suited for experimental evaluation of some basic assumptions on stereo-radargrammetry. Each stereo model was measured on a specially programmed photogrammetric analytical plotter; the resulting coordinates of ground points were compared with those from maps. It is concluded that accuracies are lower than expected at the larger stereo-intersection angles, amounting to about ±60 m in each coordinate direction. This might be explained by limitations of the quality of stereofusion caused by look angle differences and specular point migration, backscatter differences due to different incidence angles, differences in azimuth directions, and image noise and speckle.

I. Introduction

A UNIQUE SET of four radar images was obtained of an area in Argentina in repeated overflights by the Shuttle in October 1984 as part of the Shuttle Imaging Radar B (SIR-B) experiment (Fig. 1). This data set permits one to study the capabilities and limitations of radargrammetric mapping in a manner previously not possible due to a lack of available data. A comparably wide data range did not previously exist. SIR-B, however, produced radar image look-angles off-nadir from 33° to 56°, leading to stereo-intersection angles from 5° to 23° (Fig. 2).

The remote sensing and photogrammetric literature has been reporting methods of stereo radargrammetry since the work by LaPrade [5] and Rosenfield [12]. Generally these publications have either concentrated on a discussion of geometric and computational concepts, or they presented very limited experimental results with single stereo-image pairs. A comprehensive review of techniques and results was presented by Leberl [6] and updated more recently [7].

Airborne radar imagery does not lend itself well to an experimental evaluation of look-angle effects on stereo accuracies. This is caused by the fact that look angles vary greatly within a single radar image as one progresses from near to far range in order to acquire a swath greater than a few kilometers; consequently the stereo-intersection angles also vary greatly within a stereo model, and it becomes impossible to associate a statistically meaningful sample of coordinate errors with any one specific stereo-intersection angle.

SIR-B is the first opportunity to actually address the question of look angles; they vary less than 6° within a single image. They do vary, however, from one image to another. SIR-B data acquisition was designed such that incidence angles would range from 15° to 60° from one image to another over a selected target. The most diverse range of angles was obtained over an area in southern Argentina and a full experimental stereo evaluation was performed.

This paper summarizes the radargrammetric work done with this SIR-B data set. It presents geometric accuracies obtained in terrain coordinate computations, compares theoretical accuracy predictions with actual results, and discusses the applicability of radar stereo-mapping. Experimental results include the creation of digital elevation models from radar and maps, and their comparison.

Accuracy studies are based on a total of 43 points that have been identified on both maps and radar images. Smallest rms errors were about ±60 m in each coordinate direction at an intersection angle of projection rays of 18°. Theory predicted an accuracy of ±20 m. Generally the work uncovered some deviations between theoretical predictions and experimental facts. Resources for the study did not permit analyzing the reasons for these discrepancies. Therefore, we can merely speculate that the results from radar images are poorer than theory leads one to expect due to limitations of stereo viewability at larger intersection angles.

The digital elevation models are not only used for performance evaluation, but also for the creation of secondary radar image products such as radar ortho images. This paper is one in a series dealing with the SIR-B data of Argentina. Secondary image products are discussed by Domik *et al.* [3]. These products are used to map ecologic units using the characteristic backscatter signatures of various vegetation types. Thematic mapping is done by Cimino *et al.* [1]. A discussion of stereo-mapping technique and additional accuracy results from another SIR-B data set around Mt. Shasta in California are presented by Leberl *et al.* [8].

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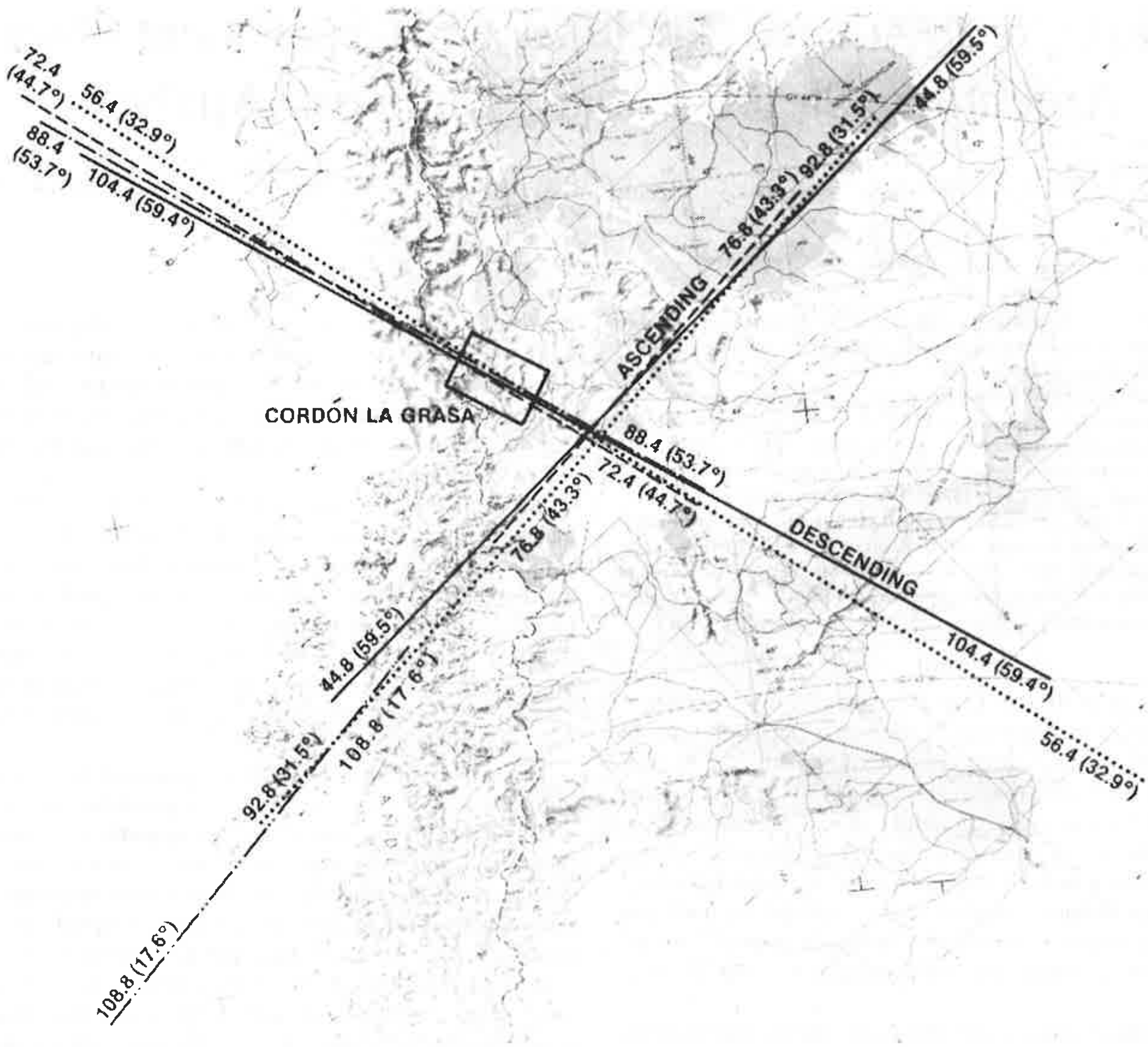


Fig. 1. Location map of the experiment site and shuttle orbits.

II. The Data Set

A. Data

Fig. 2 presents four overlapping SIR-B radar images at look angles off nadir of 56°, 51°, 43°, and 33° degrees.[1] Fig. 3 is a sketch of the imaging configurations. Included in Fig. 3 is an insert defining the radar look angle, incidence angle, azimuth angle and intersection angle. The largest intersection angle for stereoscopic parallax measurements was 23°. Image quality and the extent of overlap between pairs, however, vary sufficiently so that not all overlap pairs that one can form represent comparable stereoscopic models for the measurement of three-dimensional surface shape. Due to variations in the overlap one also has to use different groups of ground control and so-called "checkpoints" for quality evaluation. This leads to a lack of similarity in the measurements and impedes direct comparison of results.

The reference used for evaluating the accuracy of the radar generated topographic maps is a set of 1:100 000 topographic maps from the Instituto Geografico Militar of Argentina. The imaged area is in the Cordón la Grasa region of Argentina, covers a surface of 85 km × 40 km, and is described in some detail in the companion paper on the thematic interpretation of the radar images [1]. It is evident that the terrain is partly flat and partly mountainous with height differences of about 1150 m. Given conventional cartographic standards, it should be possible to extract positional information with an accuracy of up to ±20 m (rms), unless significant map generalization had been used. Rms height errors could amount to ±15 m on flat areas.[2]

B. Stereo Viewability

A great element of uncertainty in all stereo-radargrammetric work has consisted of the "viewability" of radar

[1] Note that "look-angle off nadir" is smaller than "incidence angle" due to the effect on Earth curvature.

[2] These accuracy numbers are based on the assumption that the maps conform to conventional cartographic standards.

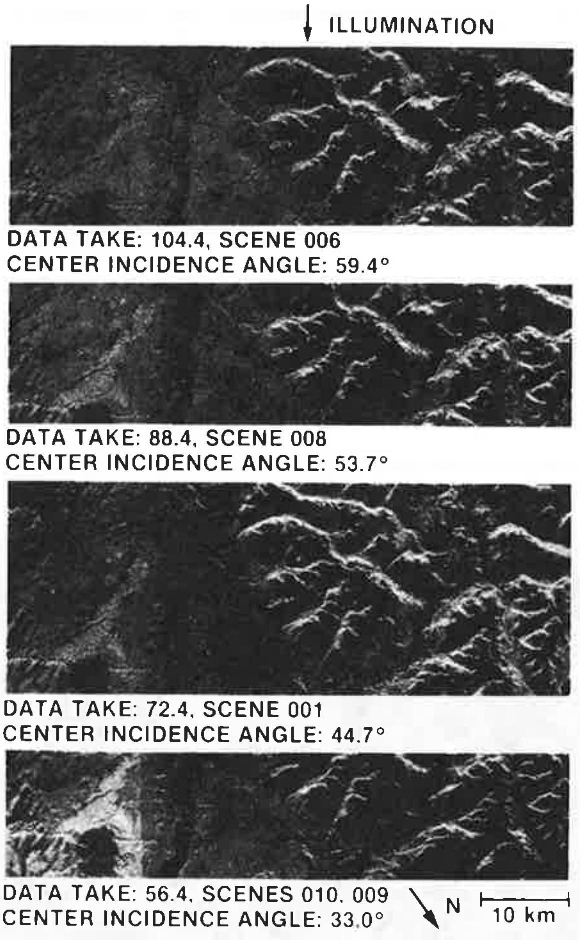


Fig. 2. Four SIR-B images, taken in October 1984 from orbit at an altitude of 250 km. Wavelength is 25 cm. Area is "Cordón la Grasa" in Argentina.

stereo models. Mathematical accuracy predictions must assume that conjugate image points in overlapping radar images can be visually matched by an observer. This ability is impeded by the fact that overlapping radar images are thematically different due to differences of illumination and due to image noise such as speckle. The extent of these differences is not well understood, except for some work with image simulations [4].

Viewability effects on accuracy could not actually be addressed in the past with real radar imagery. The current data set, however, presents a total of six stereo models as listed in Table I. Visual inspection seems to indicate that stereo viewability will be a major factor in the ability to achieve good coordinate accuracies. The stereo model at the largest intersection angle of 23° may present a different quality of stereo viewing than smaller angle data. Generally one can expect the best visual stereo matching when the intersection angles are at a minimum; unfortunately, however, this would lead to poor vertical exaggeration of the stereo model.

C. Ground Control Points

Fig. 4 illustrates the number and distribution of all points that were identified on both the maps and radar images. A total of 43 points were available for accuracy studies. Individual stereo-image pairs may only cover part of the area.

Also marked in Fig. 4 is the overlap area for which a digital elevation model was produced.

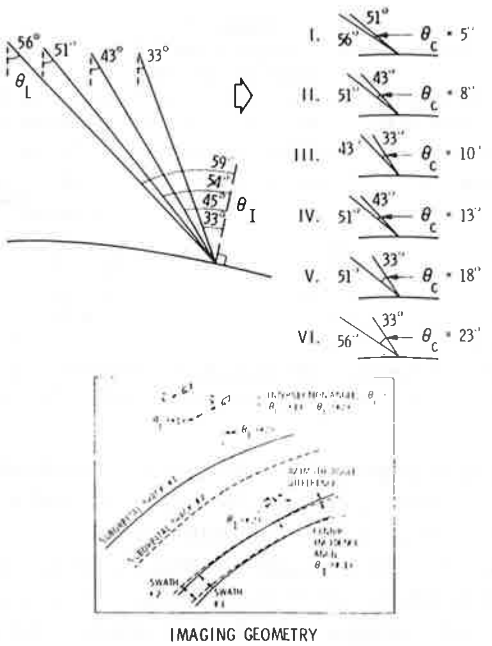


Fig. 3. Look-angle geometry of six stereo models formed by the four images of Fig. 2.

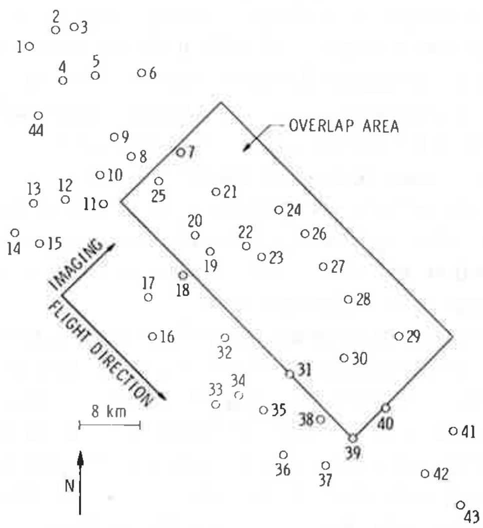


Fig. 4. Distribution of 43 ground points identified in the map at scale 1:100 000 and on the SIR-B radar images. The area of the digital elevation model shown in Fig. 7 is separately marked.

TABLE I
SIX STEREO MODELS ARE FORMED BY FOUR SIR-B RADAR IMAGES

Case	Data Takes	Look Angles	Intersection Angles
I	104 / 88	56° / 51°	5°
II	88 / 72	51° / 43°	8°
III	72 / 56	43° / 33°	10°
IV	104 / 72	56° / 43°	13°
V	88 / 56	51° / 33°	18°
VI	104 / 56	56° / 33°	23°

TABLE II
GROUND RESOLUTION IN THE VARIOUS SIR-B IMAGES USED FOR STEREO RADARGRAMMETRY
(Note that the ground resolution in range corresponds to a slant range resolution of 14 to 15 m. Values courtesy J. Curlander, JPL.)[1]

Data Take/Scene	Incidence Angle	Ground Resolution (m) (Ground range x azimuth)
56 / 09	33.1°	26 x 23
56 / 10	33.0°	26 x 23
72 / 01	44.7°	20 x 34
88 / 08	53.7°	17 x 29
104 / 06	59.4°	16 x 34

[1]It appears from personal communications during the SIR-B symposium in May 1985 that these resolution values were experimentally confirmed.

Definition of ground control points is a difficult task in radar images of natural terrain with occasional man-made features. The geometric resolution for the center region of each of the radar images is summarized in Table II. A slant range resolution of about 14 m is too coarse to produce detailed images of man-made features, for example houses, corners, bridges, street intersections, or of single trees, etc. Typically, however, these are the point features that one uses in photogrammetry and that one would also like to use in radargrammetry. The absence of an abundance of man-made details leads one to rely on drainage and topographic features; this is often not well defined in a cartographically generalized map such as that available in the project area, nor is it always easy to relate a distinct image feature to the map.

It is, therefore, not surprising that one is tempted to initially mark up many points for use as ground control points when in fact one later has to admit to a significant percentage of misidentifications.

The current experiment, therefore, clearly points to the need to develop methods of using control data that are *not* based only on point features, but also on areal features such as lakes, and on linear features such as vegetation boundaries, river courses or segments of radar reflections of a road embankment or other linear details. Finally it becomes very apparent that the contents of a map 1:100 000 do not, in general, include many of the details that the radar images show, and on the other hand describe of course a wealth of features that one cannot identify on the radar images. The degree to which maps and SIR-B images present different types of detail in the current study area is documented by Fig. 5. Therefore, it would seem to be advantageous to have available another type of reference data, preferably in the form of aerial photography.

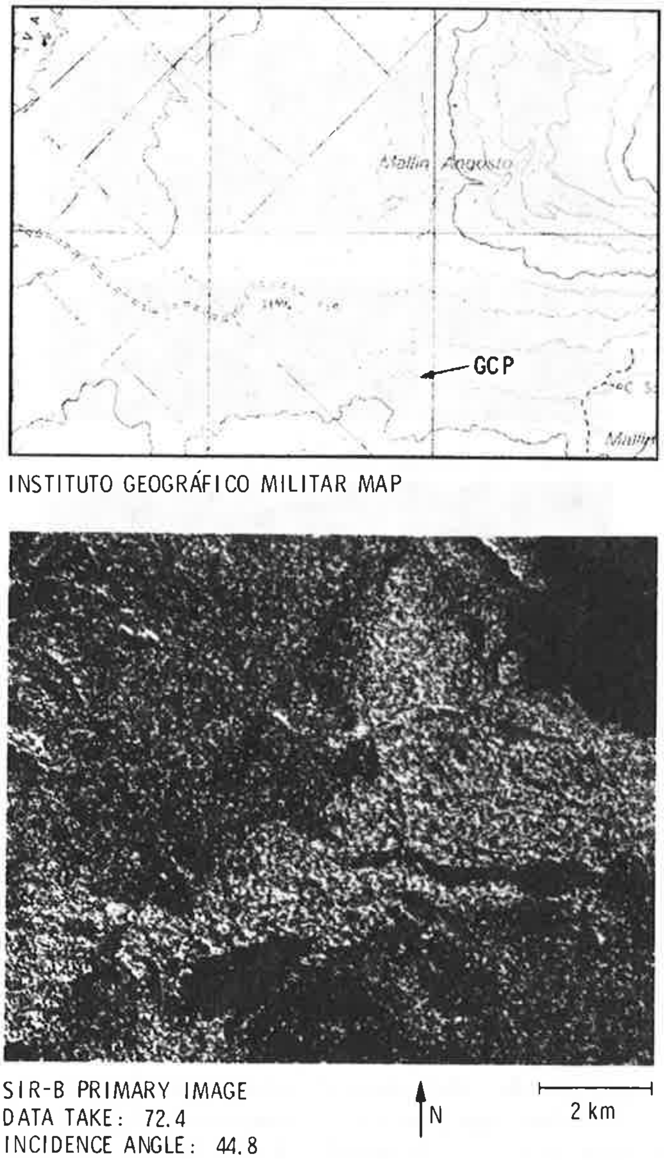


Fig. 5. Segment of the map at scale 1:100 000 and of an image with a marked ground control point.

III. MEASUREMENTS AND COMPUTATIONS

The radargrammetric measurement and computations were performed on a computer-controlled photogrammetric analytical stereo plotter. The ability to employ such an instrument with radar images has been previously described in general terms by Raggam and Leberl [10], and in more detail in the doctoral thesis of Raggam [11]. A review of the mathematical tools is contained in a companion paper on the SIR-B data analysis of Mt. Shasta [8]. The following is a summary of the presentation in that paper.

The analysis procedure consists of several steps:

Ground control points are identified on both the maps and in each of the 6 pairs of overlapping radar images.

On the computer-controlled stereo instrument a set of 18 different stereo models was "set up" or oriented and measurements of coordinates were taken. In each of the six stereo pairs three different numbers of ground control points were used.

A digital contour map was created from the most accurate of the radar stereo models and a grid was computed at a grid interval of 100 m.

A reference digital elevation matrix was obtained using the maps of the study area.

The radar- and map-derived digital elevation data were compared.

Of the total measurement area (85 km × 40 km), a subarea of about 45 km × 20 km has been stereoscopically mapped into a digital elevation model.

Computations deal with three coordinate systems: the x, y-image coordinates, the range and time coordinates r, t, and the three-dimensional system of the object space. Stereo computations consist of the stereo-model setup and subsequent data collection. Model setup begins with a transformation of measured coordinates x, y of image points into slant range r and time of imaging t. Then ground control points are projected into the image, predicting their t', r',-values. The differences Δt, Δr between predicted r', t' and measured r, t enter into a "resection-in-space," separately for each image.

This creates a preliminary link between measurements in the images and the object space; at this point a human observer has a nearly parallax-free stereo model in which three-dimensional observations of ground points are feasible. The observer now needs to clear the remaining parallaxes that might otherwise disrupt the stereo fusion, and he may need to make measurements of additional points, so called "homologue" orientation points.

Upon completion of these measurements a final least-squares computation for the stereo-model setup is performed, resulting in final values for the unknown or poorly known entities of the images, i.e., for the satellite positions and velocity vectors, the scale numbers, and time of imaging etc. As a result one now has a consistent data set in which the adjusted satellite and sensing parameters fit with the ground control data.

Data collection follows the completed stereo-model set up: one may need to collect individual ground point coordinates, polygons, elevation contour lines or a square grid digital elevation model.

The following section presents the results of measuring individual points and contour lines, and it discusses achieved accuracies by comparing the SIR-B radar-derived information with that from existing maps.

IV. Numerical Results

A. Purpose of the Numerial Work

The major questions for the radargrammetric effort are:

What order of magnitude can be achieved for the geometric accuracy of point coordinates?

How does this accuracy depend on the stereo-intersection angles?

How does the accuracy depend on the number and distribution of ground control points?

Is there a dependence of accuracy on the type of imaged terrain?

Can one obtain meaningful contour lines, and what is a proper contour interval?

In addition, the stereo-mapping work was to result in a digital elevation model to be used for the subsequent creation of secondary radar image products (see companion paper by Domik *et al.* [3].

TABLE III
Predicted Coordinate Accuracies σ_h (Height) and σ_y (Cross-Track), in Meters, for the 6 SIR-B Stereo-Image Pairs
(Only the effect of the slant range resolution $\epsilon = \pm 14$ m is considered.)

CASE	DATA TAKES	LOOK ANGLES	INTERSECTION ANGLES	σh(m)	σy(m)
I	104 / 88	56° / 51°	5°	91	68
II	88 / 72	51° / 43°	8°	52	49
III	72 / 56	43° / 33°	10°	35	45
IV	104 / 72	56° / 43°	13°	33	29
V	88 / 56	51° / 33°	18°	21	24
VI	104 / 56	56° / 33°	23°	18	18

B. Theoretical Predictions of Coordinate Accuracies

Extensive studies have been performed in the past regarding the propagation of image errors into an error of computed ground coordinates. The most typical and important image errors derive from the slant range resolution ϵ. The range resolution causes a standard deviation of slant range r denoted by σ. If we assume that the slant range errors are normally distributed, we find for the standard deviation

$$\sigma_r = \epsilon/2. \tag{1a}$$

In the event that the slant range errors were uniformly distributed in the range resolution interval, the standard deviation would be

$$\sigma_r' = \epsilon/2\sqrt{3}. \tag{1b}$$

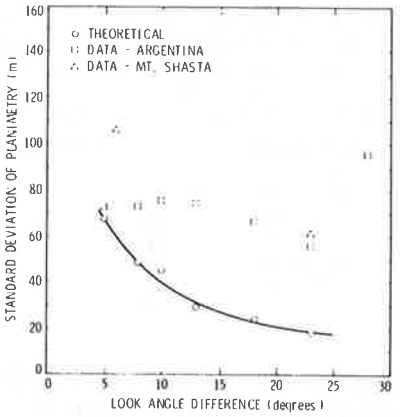
According to Leberl (1979), range errors propagate into standard derivation of the terrain height coordinate σ_h and of the across-track horizontal coordinate σ_y as follows:

$$\sigma_h = \sigma_r \frac{\{(\sin \theta'^2 + \sin \theta''^2)^{1/2}\}}{\sin (\theta' - \theta'')} \tag{2a}$$

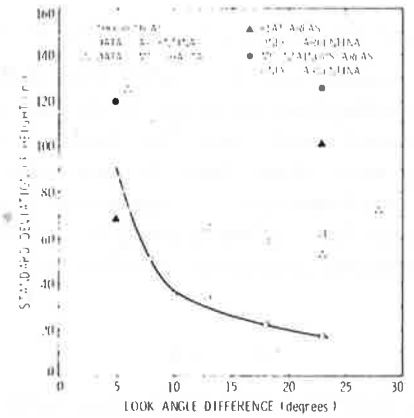
$$\sigma_y = \sigma_r \frac{\{(\cos \theta'^2 + \cos \theta''^2)^{1/2}\}}{\sin (\theta' - \theta'')} \tag{2b}$$

Variables θ', θ'' are the look angles on the two data sets. The equation does not consider the errors of the stereo model other than those caused by range resolution limitations. It also deals with σ_r, the limitation due to range resolution, and not with error of observed stereo parallaxes.

Table III presents predicted errors of terrain height σ_h and of cross-track coordinate σ_y assuming a range resolution of ± 14 m and normally distributed range errors. It is evident that height errors are expected to be ± 90 m in the case of small intersection angles of 5°, and ± 18 m for the 23° intersection angle. The size of the radar image pixel is of no concern in this context. SIR-B presents images with pixels of 12.5 m × 12.5 m irrespective of the range and azimuth resolutions.



(a)



(b)

Fig. 6. Planimetry (a) and height (b) accuracy versus stereo-intersection angles, both as predicted and obtained experimentally. The numerical accuracies from random terrain points are shown separately by triangular symbols.

C. Practical Results

Each of the six stereo models was set up three times, with 2, 4, and all identifiable ground control points, leading to a total of 18 computed sets of coordinate accuracies.

Table IV is an overview of all computed cases. Contrary to the theoretical values, there is an unexpectedly *small* variation in accuracy, whatever the stereo-intersection angles. Fig. 6 illustrates graphically the change of accuracy as a function of stereo-intersection angle: the results at a 5° intersection are nearly as predicted, at 23° the experimental data are poorer than those expected. Fig. 6 is based on Table IV *and* on the results from a different data set of Mt. Shasta (see the compansion paper by Leberl *et al.* [8]).

In order to better understand the significance of this discrepancy a set of terrain heights was sampled at random locations in the stereo models at 5° and 23° intersection angles. The heights were also extracted from the maps using the latitude and longitude coordinates of the measured points. The results, shown in Table V and in Fig. 6 confirm the results from ground control points; however, if the terrain is essentially flat, as is the case in part of the stereo model, then the height errors tend to be smaller. It is in the mountainous areas that the limitations of stereo accuracy are more apparent.

TABLE IV
ROOT MEAN SQUARE ERRORS OF GROUND COORDINATES, IN METERS, AS OBTAINED FROM STEREO RADAR IMAGE PAIRS
(Input are 4 orbit positions in each image.)

CONTROL POINTS	CASE	INTERSECTION ANGLE (°)	COORDINATE ERRORS IN METERS			
			NORTH	EAST	HEIGHT	POINT
2	I	5	72	85	101	87
2	II	8	86	76	116	94
2	III	10	91	100	119	104
2	IV	13	87	121	89	100
2	V	18	65	110	71	84
2	VI	23	88	56	82	77
4	I	5	76	96	99	91
4	II	8	89	74	118	95
4	III	10	77	95	89	87
4	IV	13	82	113	87	95
4	V	18	70	86	66	74
4	VI	23	72	80	77	76
17	I	5	67	78	86	77
18	II	8	78	70	110	88
15	III	10	65	85	67	73
26	IV	13	77	73	65	72
10	V	18	59	74	59	64
10	VI	23	62	49	62	59

TABLE V
ROOT MEAN SQUARE HEIGHT ERRORS FROM DIFFERENCES BETWEEN STEREO-RADAR AND MAP
(Flat and mountainous areas are considered separately.)

Stereo case	Intersection angle	Flat area		Mountainous	
		Terrain Heights	RMS +Error (m)	Terrain Heights (m)	RMS Error (m)
I	5°	275	69	1150	120
VI	23°	275	108	1150	125

Tables IV and V are the basis for a set of conclusions on the major accuracy questions. The limitation of available resources for the analysis only permits speculation on the reasons for the discrepancies between theory and actual data. A fuller explanation of the discrepancies must await additional work.

1) Order of Magnitude for the Accuracy: It is evident that terrain coordinates are less accurate than theoretical prediction based on range resolution did indicate. This difference becomes more distinct as stereo-intersection angles increase. One might argue that the limitations are due to:

1) effects of "specular point migration" and migration of edges due to differences in illumination;
2) changes in backscatter due to differences in incidence angles;
3) variations in orbit azimuths and resulting edge migration;
4) effects of noise.

Another factor might be the insecurity introduced by the maps. It is possible that ±0.5 mm accuracy is the limit for the map due to map generalization and other factors. This would convert to ±50 m on the ground and could also obscure the accuracy of the stereo-radar system (see Fig. 6).

2) Effect of Stereo-Intersection Angles: Vertical exaggeration q increases from $q = 0.35$ at 5° intersection angles to $q = 1.4$ at 23°. The accuracy also increases; we find, however, that this is less than was predicted. Speckle and its effect on stereo-radar pointing accuracies have not yet been a subject of study. The effect of illumination differences on ease of stereo-viewing has been studied in the past by Kaupp *et al.* [4], and Domik [2]; however, no indication did so far exist that the end of the SIR-B range of intersection angles at 23° would significantly impair stereo fusion. The single SIR-B sensor, resolution, and speckle characteristics, as well as potential errors in the available maps may just not permit one to draw firm conclusions on this effect. In order to better utilize radar images, this effect needs to be better understood and future work needs to be planned.

3) Ground Control: Accuracies do not depend significantly on the number of control points used; this is not suprising since a satellite sensor provides for good geometric stability.

4) Imaged Terrain: There is an obvious relationship between topography and accuracy, although this contradicts photogrammetric principles. The dependence is evident from Table V. First in flat areas there is less confusion introduced by differences in the illumination angles. Second, an operator might have more height cues such as micro relief and cultural features. Third, he might in a flat area not change the height setting and, therefore, produce smaller errors than if truly independent sets of measurements were to be made.

D. Digital Elevation Models and Contour Lines

The data sets can be used to create a description of the terrain surface, either in the form of a square grid digital elevation model (DEM), or in the more traditional form of contour lines. A relevant question concerns the intervals between contour lines, and the mesh size of the DEM.

Classical cartographic standards in the United States indicate that 90 percent of all interpolated heights must have errors smaller than half the contor interval. This converts to the statement that the contour interval needs to be larger than 3 times the standard height error. European cartographers are more conservative and request this ration to be about 5.

The height accuracies from SIR-B images of ± 60 m lead to a recommended contour interval of 200 m. One could compute contour lines from DEM's at smaller intervals; however, the result would not compare to traditional standards.

Fig. 7 shows the map-derived contour lines and a contour map produced from the stereo model of case V at 18° intersection angle. This was chosen since the overlap area in that case is larger than in case VI. The map area is slightly shifted with respect to the radar stereo coverage. The overall terrain shape is represented correctly on the radar derived contour lives; geomorphological detail cannot be obtained from stereo parallax measurements. But this is evident from the accuracy predictions alone.

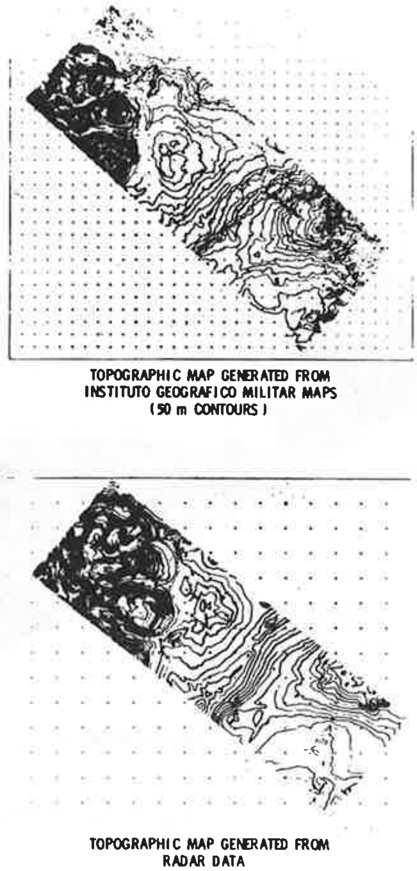


Fig. 7. Contour map produced from the stereo-model case V at 18° intersection angle, at a contour interval of 200 m, and from the map. Note that the two plots do not show the exact same area.

In order to quantify the difference between map and radar, Fig. 8 shows a square grid DEM in an axonometric view. The mesh size of a DEM is not a subject of cartographic standards. However, it is obvious that the grid spacing must be significantly larger than the height accuracy if one does not simply oversample the terrain surface. It is of interest to compare the radar derived DEM with one obtained from the map (Fig. 9). The comparison is with the help of a difference-DEM, shown in Fig. 10, that presents the difference in each grid point between the radar height and that computed from the map. A visual inspection of this difference-DEM shows that height errors are of the same order magnitude, whether one deals with flat or mountainous terrain. However, the autocorrelation of the errors is clearly dependent on the type of terrain. The rms differences of the heights amount to ± 84 m.

The digital terrain data can be employed in the creation of seconary radar image products such as geometrically rectified ortho images or radiometrically corrected backscatter images. This is discussed in a companion paper by Domik *et al.* [3].

V. Conclusions

The multiple-look-angle data set collected by SIR-B in Argentina for the first time permits the assessment of to-

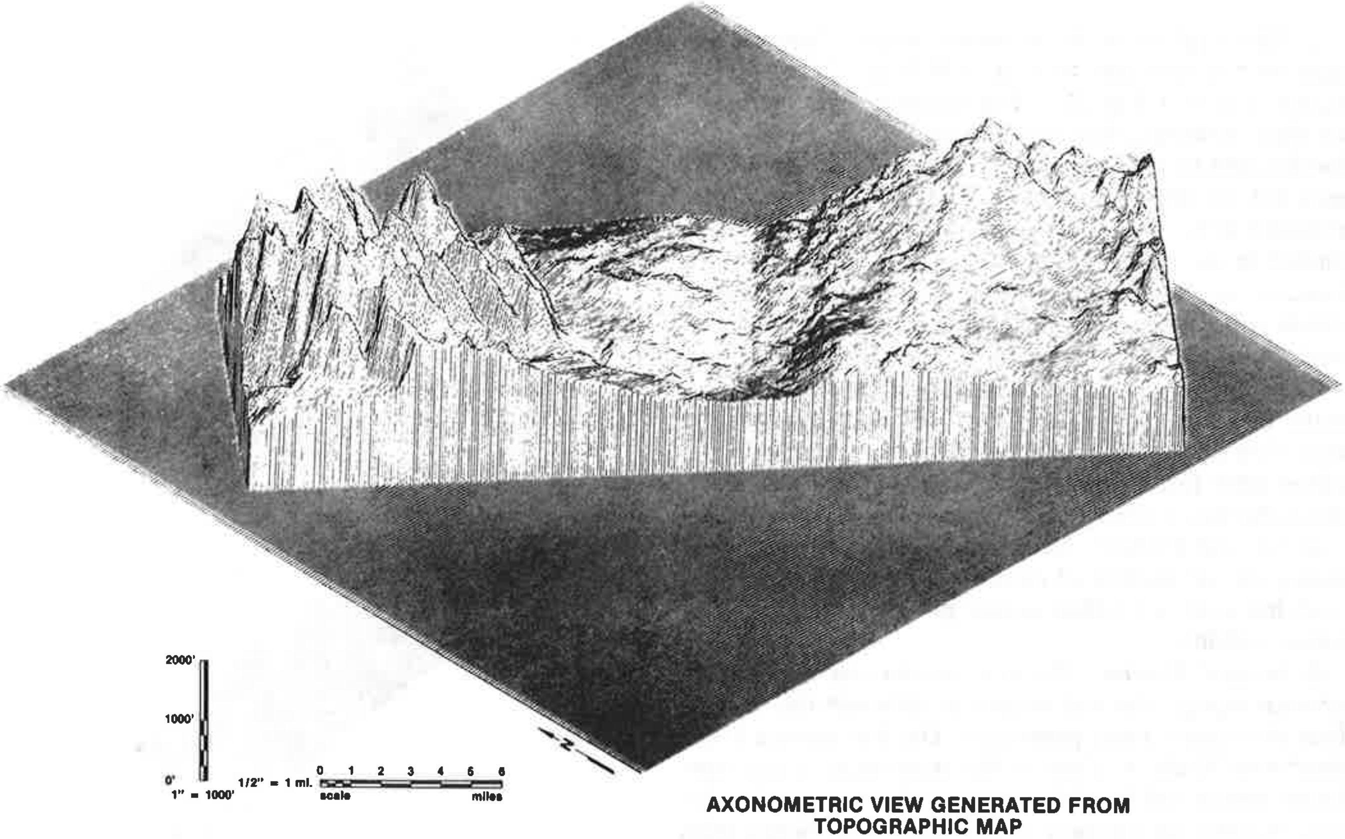


Fig. 8. Axonometric view of a square grid DEM obtained from case V. Grid mesh interval is 150 m.

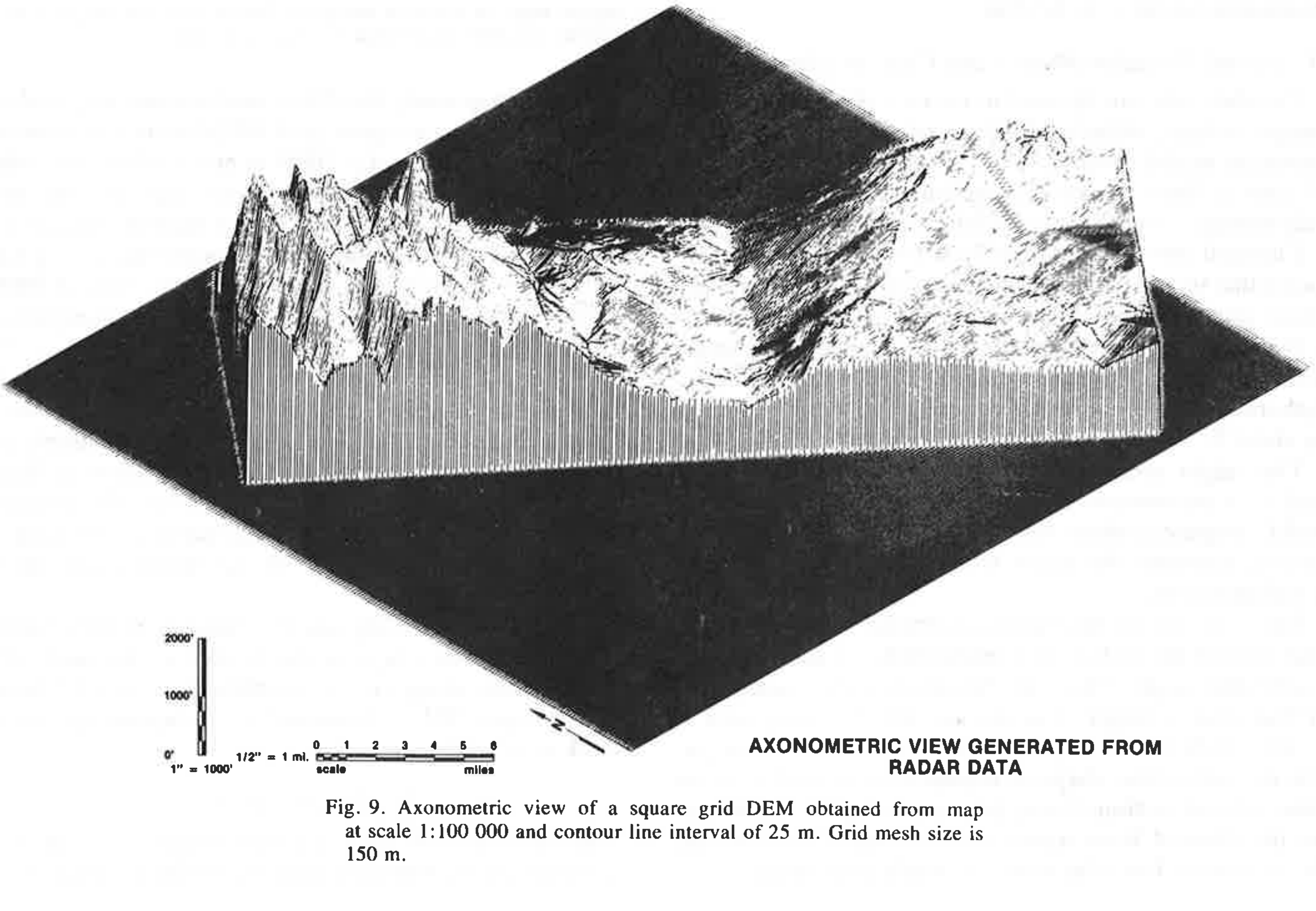


Fig. 9. Axonometric view of a square grid DEM obtained from map at scale 1:100 000 and contour line interval of 25 m. Grid mesh size is 150 m.

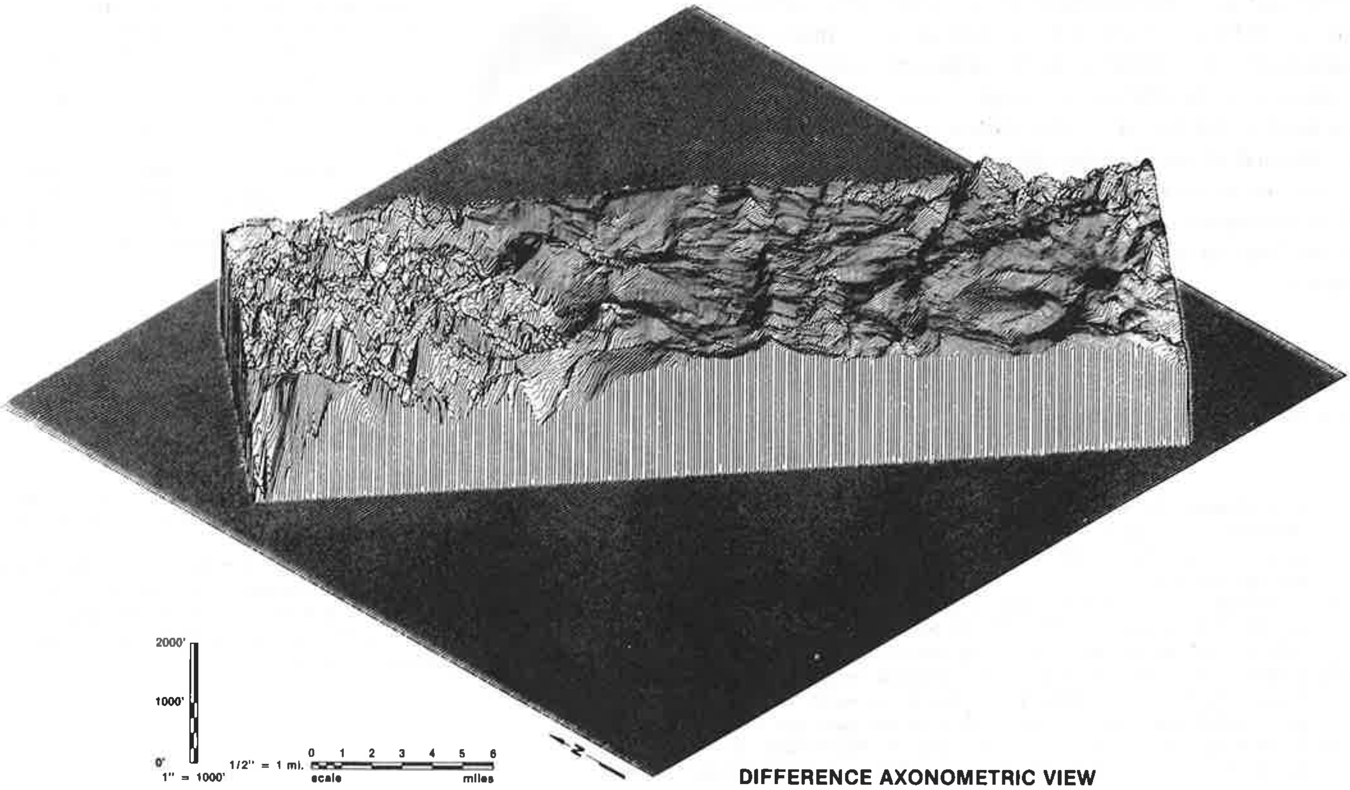


Fig. 10. Axonometric view of the difference of DEM's from radar and map. Grid mesh size is as in Fig. 8.

pographic mapping accuracy as a function of radar intersection angle. The images form six stereo models with stereo-intersection angles between 5° and 23°. Stereo-radargrammetric measurements were taken and compared with known ground data taken from maps at scale 1:100 000. Since a comparable data set has not existed previously it was of interest to investigate the influence of stereo-intersection angles onto the accuracy of ground point coordinates, and onto the digital elevation models (DEM's).

The experimental results do not conform well to predictions based on slant range resolution values of ± 14 m alone, except at small 5° intersection angles where an error of ± 92 m is expected. At 23°, the range resolution would convert to a height error of ± 18 m. SIR-B height results at identifiable ground control points are ± 100 m at 5° intersection and ± 60 m at 23°. Heights at random locations (as opposed to identifiable control points in mostly flat areas) in mountainous parts of the stereo model differ from those of the map with ± 121 m at 5°, and ± 126 m at 23°. This includes a significant effect of horizontal errors on height.

A full explanation of the differences between theoretical prediction and experimental results would require that:

1) the effect of look-angle differences on stereoscopic pointing be also studied in a more quantitative manner than thus far possible;
2) the effect of azimuth differences on stereoscopic pointing be analyzed;
3) the effect of speckle on pointing in the stereo model be well understood;
4) ground information be available at a higher accuracy than that obtainable from generalized maps at scale 1:100 000.

The stereo-image pairs permit one to create digital elevation models (DEM's) and contour line plots of the study area. A meaningful contour interval is 200 m; the DEM grid mesh size of 150 m may be too dense, considering that a random error of ± 60 m exists in each individual value. The DEM does not contain the microdetail of the terrain surface. Essentially, therefore, the accuracy limitation leads only to a description of the major topographic features.

Improved accuracies and resolution of detail may be feasible regarding microfeatures: current methods of stereo radargrammetry only address the measurement of geometric disparities and computation of heights from stereo parallaxes. An additional concept consists of the computation of terrain slope values from a redundant set of multiple gray values obtained in each pixel from the overlapping images. This would require that the images be registered to within one pixel. Such registration presupposes that stereo parallaxes be known and can, therefore, be removed. An avenue of further refinement for the extraction of topographic features from overlapping radar images is, therefore, the combination of parallaxes and slope-from-shading techniques. This concept might need to receive attention in the future since illumination differences act as a perturbation for parallax observation, but are a source of shape information in slope-from-shading techniques. Limitations of this approach would obviously consist due to effects of image noise such as speckle. However, we found that parallax measurements can be performed at small stereo-intersection angles with accuracies that seem to be close to theoretical predictions. We also anticipate that multiple brightness values in each pixel permit one to remove the speckle effect on the slope computation.

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