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APPLICATION OF IMAGING RADAR TO MAPPING

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ABSTRACT

The present state of mapping with radar is reviewed. Emphasis is on radargrammetric mapping with single images, stereo pairs and block adjustment. Applications to thematic mapping are addressed as well. Examples presented concern radar mosaicking, sea-ice study and extraterrestrial mapping (Moon, Venus).

I. INTRODUCTION

The application of side-looking radar images to topographic mapping had been studied intensively and nearly exclusively at military agencies until a few years ago. Civilian research at that time was limited. However, while the study of military radar mapping until recently seems to have been deemphasized, it is being considered for civilian tasks. A number of operational mapping projects have been carried out with radar in different regions of the world. Brazil's RADAM project is the largest of these. At the same time the importance of radar is being evaluated as a remote sensing tool to be used in conjunction with other data. This is particularly signified by considerations for radar imaging from satellites (Seasat-A, Space Shuttle and Space Lab, Venus Orbital Imaging Radar).

Simultaneously, research is taking a closer look at the capabilities and limitations of radar imaging for remote sensing of subsurface features, surface roughness, soil moisture, polarization anomalies, etc. Mapping with radar is thus a developing field of study with valuable present applications and future promise.

This short review will go over the basics of radargrammetry, addressing the projection equation, stereo-radar and image block adjustment. Then recent work will be reviewed concerning the applications of radargrammetric mapping to cartography, with references to measurements of sea-ice drift and marine mapping.

II. SINGLE IMAGE RADARGRAMMETRY

A. Mathematical Expression

Radargrammetric projection equations have been formulated on many occasions in the literature. It is essential to differentiate between real-aperture and synthetic-aperture imaging. In both cases the basic fact remains that radar projection lines are circles concentric with respect to an antenna (Figure 1). However, with brute force radar (real-aperture) the plane of a projection circle is normal to the longitudinal antenna axis, while with synthetic-aperture radar (SAR) it is normal to the velocity vector of the antenna. From Figure 2 one may thus specify the following projection equation:

$$\underline{p} = \underline{s} + \underline{A} \cdot \underline{r} \tag{1}$$

where $\underline{p}$, $\underline{s}$ are vectors in an object space coordinate system defined by unit vectors $\underline{x}$, $\underline{y}$, $\underline{z}$, while $\underline{r}$ is a vector in an image space coordinate system defined by unit vectors $\underline{u}$, $\underline{v}$, $\underline{w}$, and $\underline{A}$ is a rotation matrix.

The unit vectors, $\underline{x}$, $\underline{y}$, $\underline{z}$, are fixed to the imaged object, while the unit vectors $\underline{u}$, $\underline{v}$, $\underline{w}$ are fixed to the radar antenna.

The vector $\underline{r}$ is a function of slant range r, look angle Ω and a system constant ϕ (squint):

$$r = r(\sin \phi,\ (\sin^2\Omega - \sin^2\phi)^{1/2},\ \cos \phi) \tag{2}$$

The matrix $\underline{A}$ describes the rotation of the image system $\underline{u}$, $\underline{v}$, $\underline{w}$ into the object system ($\underline{x}$, $\underline{y}$, $\underline{z}$). It is defined by the classical ρ, ω, ψ angles of photogrammetry, provided however that real-aperture radar is considered. For SAR it is a function of the velocity vector $\dot{\underline{s}}$ of the antenna.

Further details may be found in the literature (Leberl, 1975e, 1978; Leberl et al., 1967a). It may be interesting to note that the radargrammetric difference between real-aperture and SAR has so far not been considered in a majority of radargrammetric studies. A recent valuable exception dealing with satellite SAR is the paper by Kratky (1979).

B. Accuracies

Single image radar mapping accuracies achieved in the past depend on a number of factors of a particular project or experiment: type of radar system, resolution, stabilization, density of ground control, type of control, mapping method, type of terrain. Therefore results of one study may not be generalized.

The term "accuracy" describes the geometric errors of mapping. In a study one can check these errors using checkpoints and computing root mean square errors m_x, m_y in the coordinate directions x and y. These error components can be combined into a single point error m_p:

$$m_p^2 = m_x^2 + m_y^2.$$

Actually achieved point errors m_p are plotted in Figure 3; it is clear that accuracies can vary widely as a result of project parameters. Details have been discussed in the literature (e.g., Leberl, 1976b).

In the best cases published accuracies were of the order of the ground resolution. Such results were reported, e.g. by Gracie et al. (1970), where very high density of well identifiable ground control was available (about 10 points per 100 sq km).

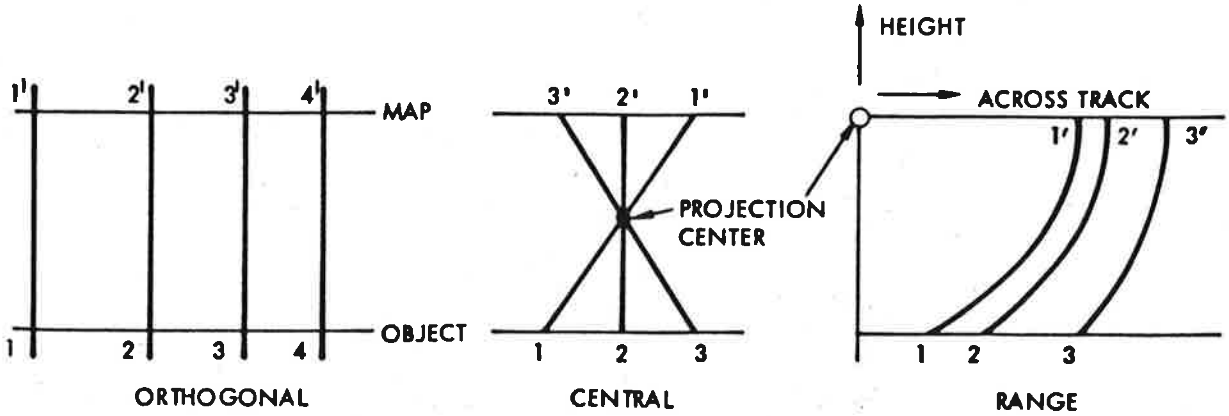

Figure 1. Projection lines for (a) the orthogonal, (b) the central and (c) the radar range projection. Note that projection lines are circles in case (c).

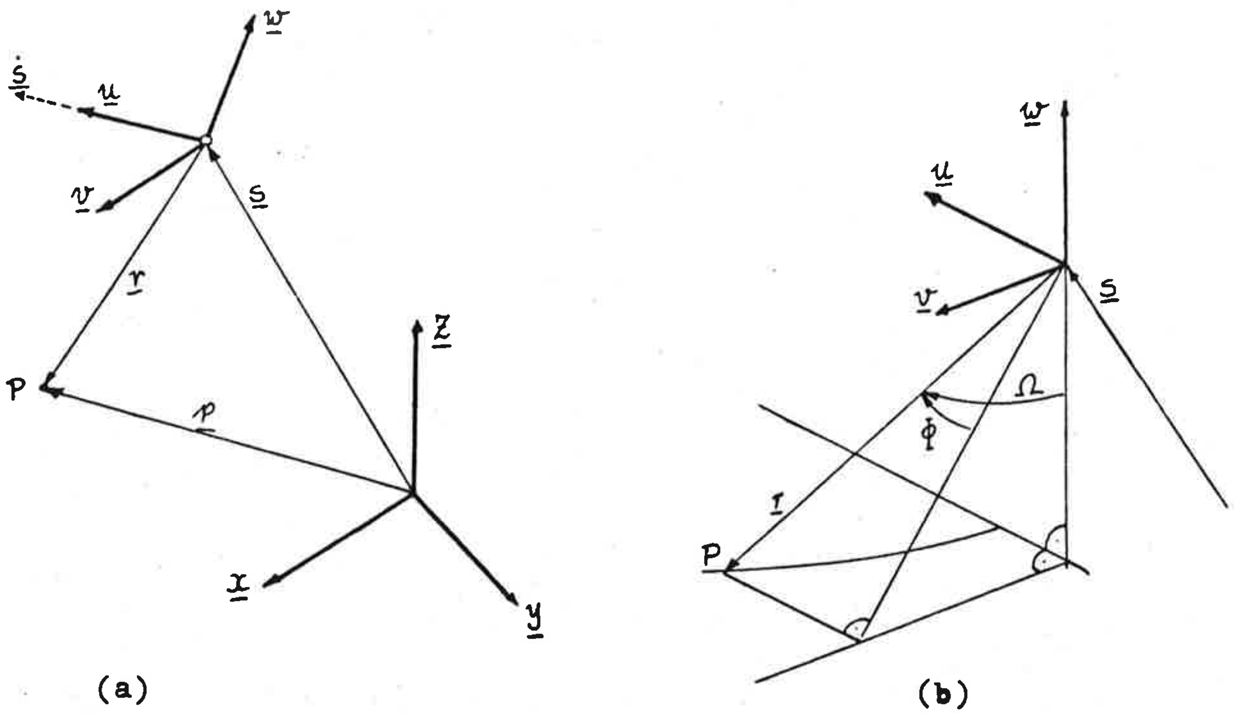

Figure 2. Definition for the radar projection equations.

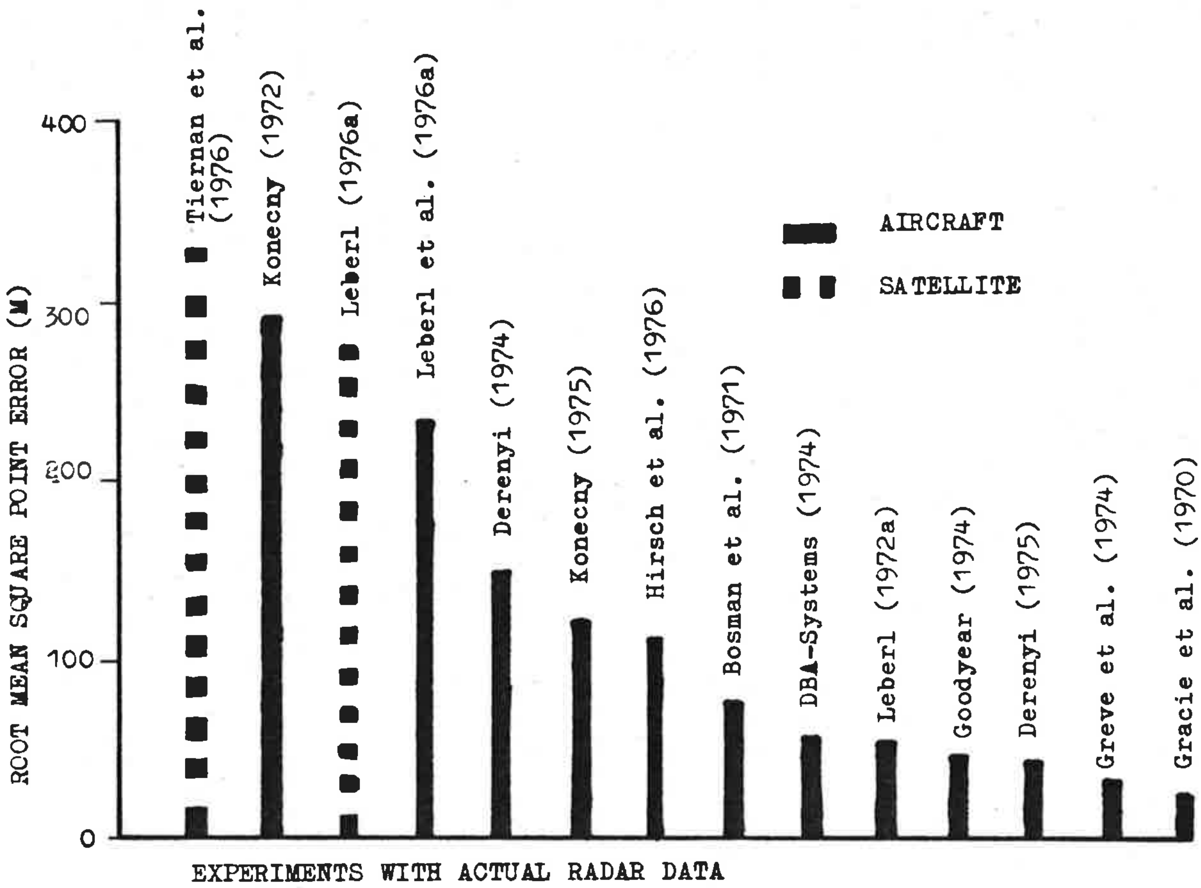

Figure 3. Accuracies achieved with single image radar mapping. Results depend strongly on specified project parameters. Satellite results are from the Apollo 17 mission to the Moon in 1972.

"Ground resolution" is here understood as the minimum distance that two reflectors must have on the ground to produce separate images. A value for the ground resolution is usually provided by the equipment operator and often is a result of confusion when comparing radar systems of different manufacturers, or when comparing radar with other imaging techniques.

C. Rectification

Rectification is the transformation of the single radar image into a map projection. The process is usually photographical, but can also be numerical or graphical or any combination of the above. Using Eqs. (1) and (2) with measured navigation data does enable one to transform a given radar image point into the map coordinate system (whereby the ground height must be known or assumed to be known). If in addition to navigation data ground control points are also available, then the set of transformed radar image points can be matched to these control points. Generally this match may be done with some sort of interpolation algorithm and many different procedures are possible and have been applied in the past.

While numerically the possibilities for rectification are boundless, they are limited in practice if the photographic image is to be reproduced with correct geometry. The technology of digital image processing permits complete flexibility for rectification (see Figure 4). All geometric corrections are possible; however, this rectification is presently expensive and tedious and therefore unsatisfactory for any large mapping effort.

Jensen (1975) described an optical rectifier for image strips that permitted changes to the along versus across track scales. The instrument employed anamorphic lenses. Its performance was such that the rectified images were of degraded quality; rectification was partial only (along track scale), and the solution was therefore unsatisfactory.

Peterson (1976) has extended the optical correlator (for SAR) to achieve correction of along track scale. The solution is straightforward and does not degrade image quality. Rectification of along track scale is achieved during the conversion of signal films to map films. The simplicity of this method makes it attractive. However, it only applies to SAR. Its implementation requires prior numerical computation to determine the amounts of image deformations. On the basis of this computation, curves can be produced for the along track scale (Figure 5).

An ortho photo-production capability for radar was developed by Leberl and Fuchs (1978) and recently applied by Leberl et al. (in press) to a series of radar images. The equipment used is the Avioplan OR-1 manufactured by Wild of Heerbrugg, Switzerland. Similar instruments exist also from other manufacturers. A result is illustrated in Figures 6a, b.

III. RADAR STEREO MAPPING

A. Visual Stereo

Stereo viewing of overlapping radar imagery can greatly enhance the interpretation of the images by providing an improved means to observe morphological details (Koopmanns, 1974), to determine slope angles and height differences and

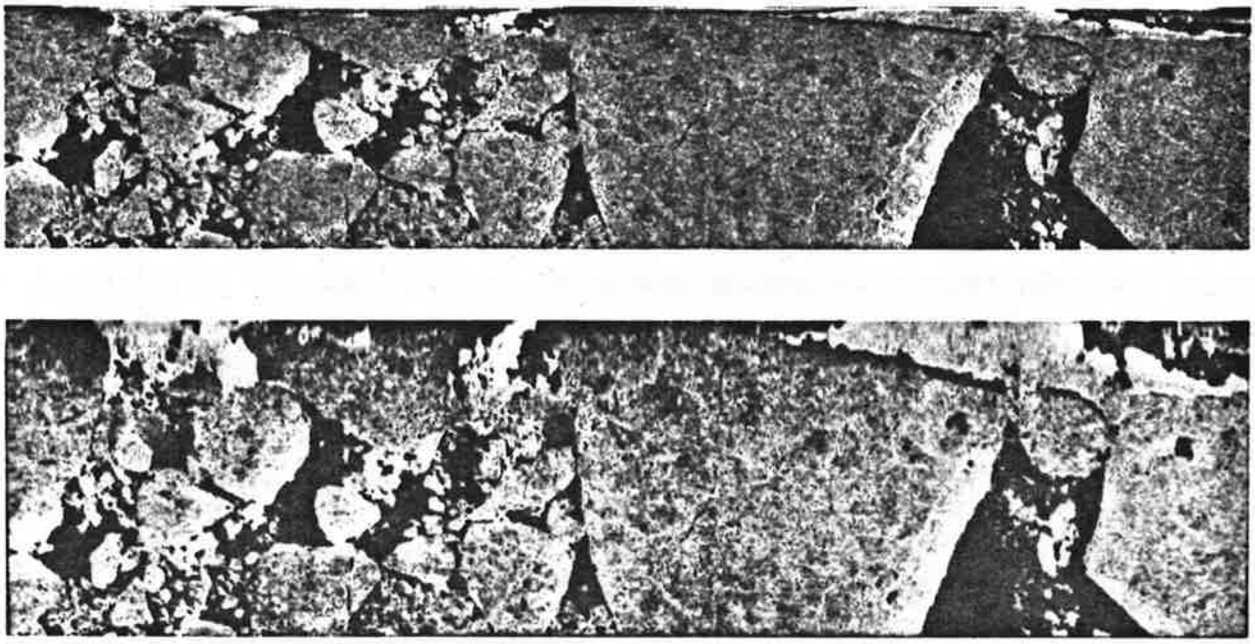

Figure 4. Example of radar image rectification using digital image processing. The distorted image (a) is in slant range presentation. Rectification is mainly a transformation to ground ranges.
(Images courtesy Jet Propulsion Laboratory, taken with L-band synthetic aperture radar system over arctic sea ice.)

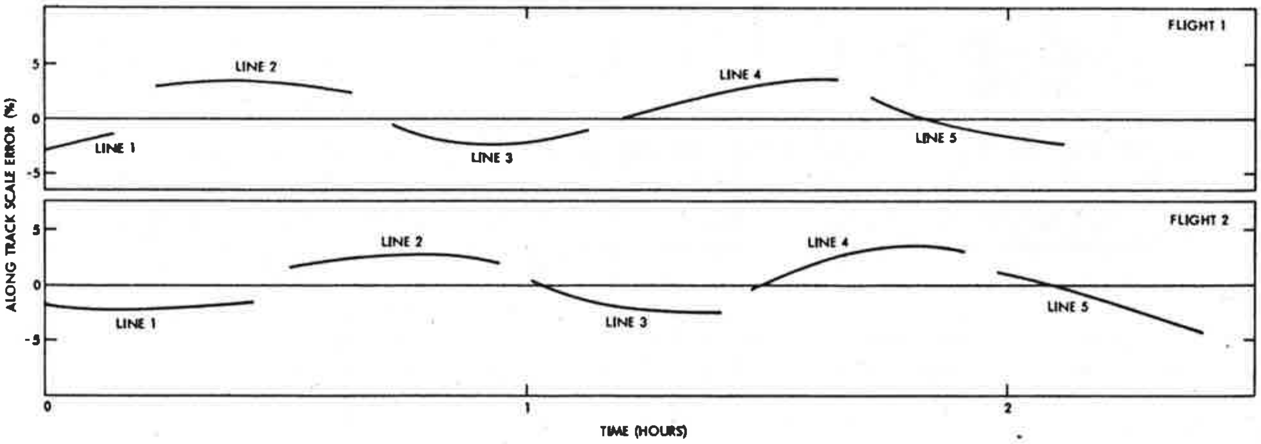

Figure 5. Scale error curves found in radar image strips (Leberl, Jensen and Kaplan, 1976). The periodicity of the along track scale errors as function of time is obvious.

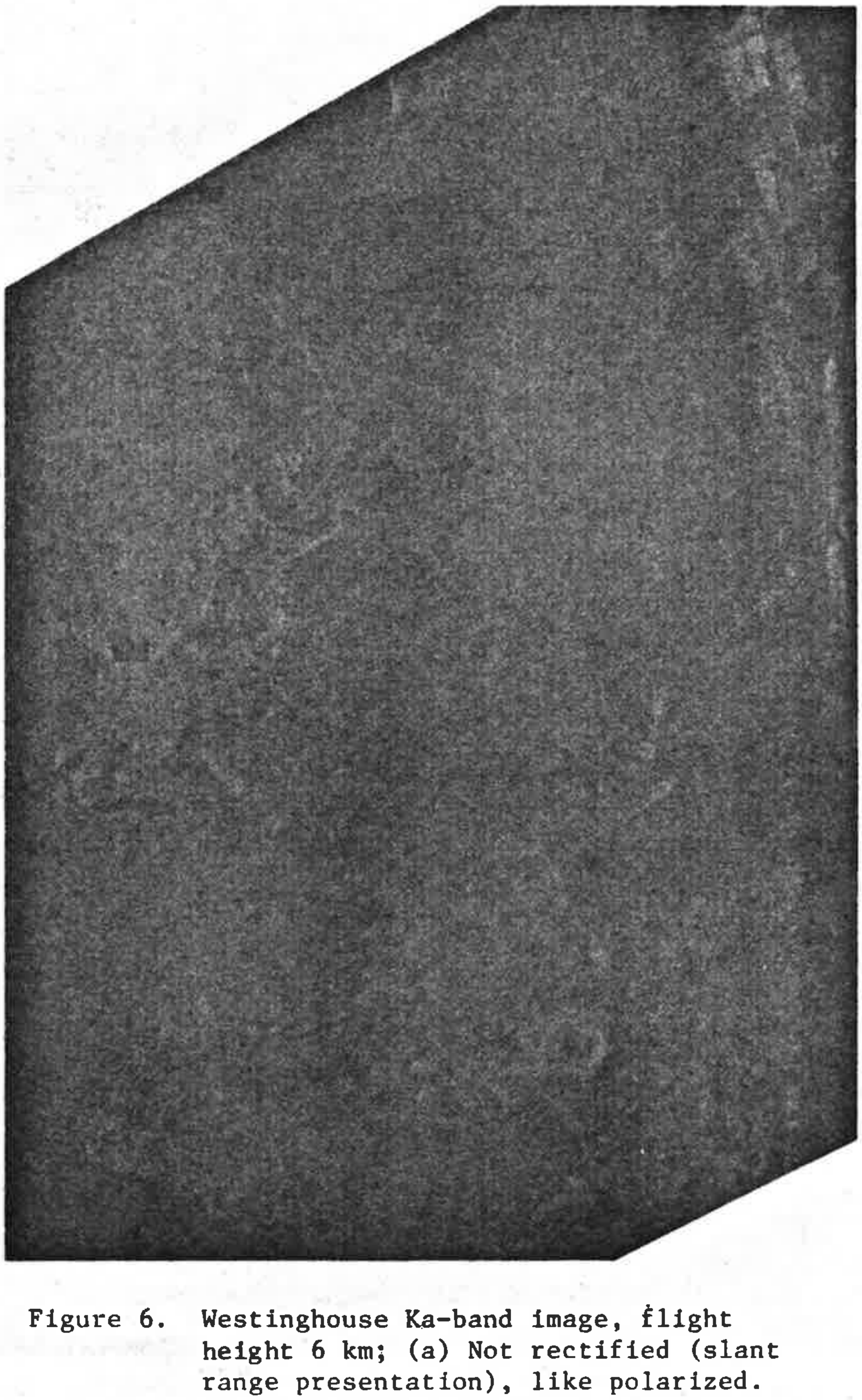

Figure 6. Westinghouse Ka-band image, flight height 6 km; (a) Not rectified (slant range presentation), like polarized. (b) Rectified on photogrammetric orthophoto-machine, cross-polarized.

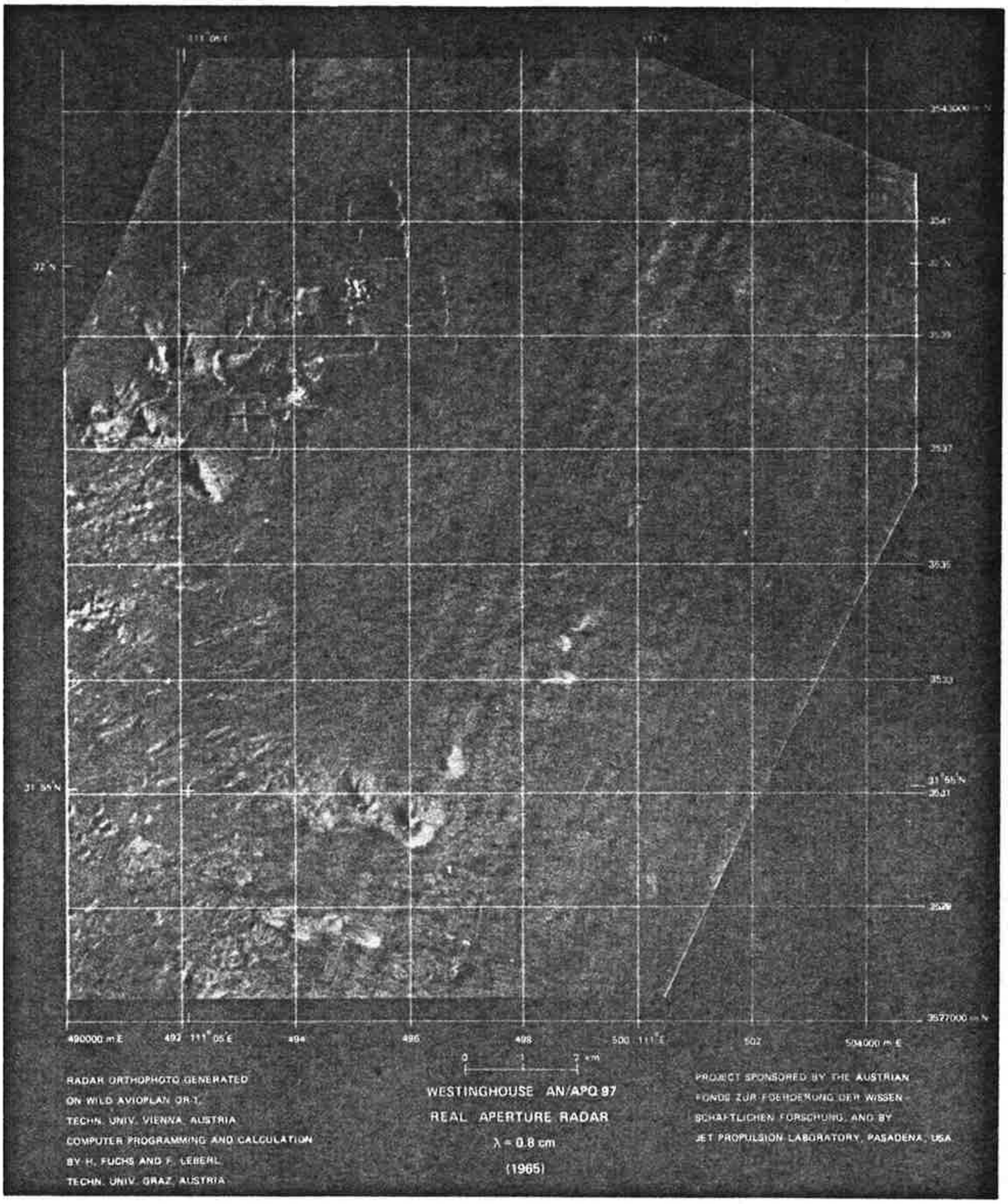

Figure 6 (Contd)

to improve cartographic mapping and point positioning accuracies. The present state of knowledge was reviewed by Leberl (1979).

A number of different schemes are conceivable to produce overlapping imagery in such a way that visual stereo is possible. Figure 7 illustrates the most common ones: same side and opposite side (La Prade, 1963; Rosenfield, 1968). These schemes are the only ones possible for synthetic aperture radar. Crosswise intersecting flight lines do not seem to produce valid visual stereo (Graham, 1975b). Other types of stereo arrangements would be possible with real aperture radar, for example, with convergent schemes using tilted antennas (Leberl, 1972b; Bair and Carlson, 1974).

In order to view a three-dimensional model the two images comprising the stereo pair must be sufficiently similar: the image quality and object illumination must be comparable and the geometric differences (parallaxes) must not exceed a certain maximum. In photography this hardly ever presents a problem since sun angles do not change drastically in overlapping photos. In radar images however the illumination angles depend on the orientation and position of the sensor and so does the appearance of the images.

Figures 8 to 11 present examples of radar stereo pairs demonstrating some of the limits to stereo viewing. Figure 8 shows part of the Estrella mountains in Arizona, U.S.A., imaged with an opposite side arrangement from an aircraft at 12 km altitude. It can be seen that slopes that reflect strongly in one image are in the radar shadow in the other image. A stereo impression can be obtained in the flat areas of this stereo pair, but becomes very difficult in the mountains. Figure 9 demonstrates with the same side stereo pair taken with the same radar system that there are no problems to stereo viewing.

Figures 10 and 11 present two Apollo 17 satellite radar stereo pairs taken of the lunar surface with same side geometry and very small stereo base. Look angles, however, are much steeper than in the examples of Figures 8 and 9. This leads to larger relief displacements and to differences of image contents in stereo mates even with small stereo bases. In the flat part of Figure 10 stereo viewing is not difficult. However, in the Apennine Mountains stereo fusion becomes nearly impossible and this is even more difficult in the image taken over the rugged Oriental region on the Moon's far side (Figure 11). From the above examples, the following factors influencing radar stereo viewing can be identified:

Stereo arrangement (same side, opposite side).
Look angles (angles off-naidr).
Stereo intersection angles.
Ruggedness of the terrain.

Exact interrelations among these factors are presently not well understood. Past experiences lead, however, to the tentative conclusion that opposite side stereo can only be applied in cases of flat or rolling surfaces, while rugged terrain requires same side imaging. Stereo viewing improves with shallower look angles (45° off-nadir and more). With steeper look angles (near nadir), the stereo base has to be reduced for successful stereo viewing, otherwise the differences of relief displacement become too large (compare Fig. 11). This smaller stereo base while improving the stereo viewability, does degrade the accuracy of the stereo

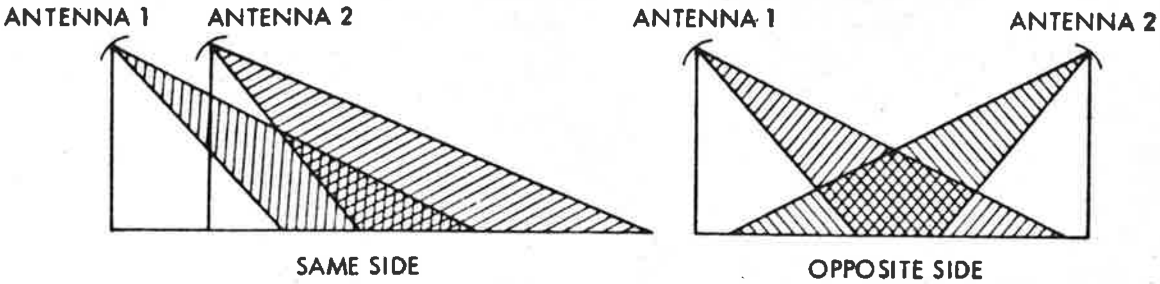

Figure 7. Basic flight configuration for stereo radar.

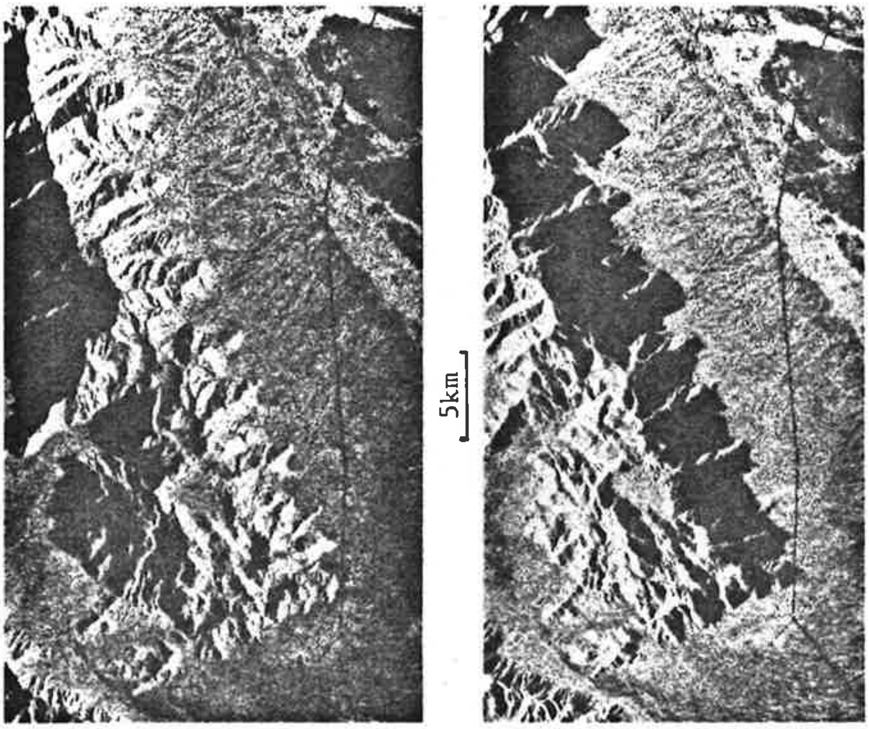

Figure 8. Aircraft stereo radar image pair, opposite side geometry. X-band, 12 km altitude; Estrella Mountains, Arizona (Courtesy of Aeroservice, Goodyear)

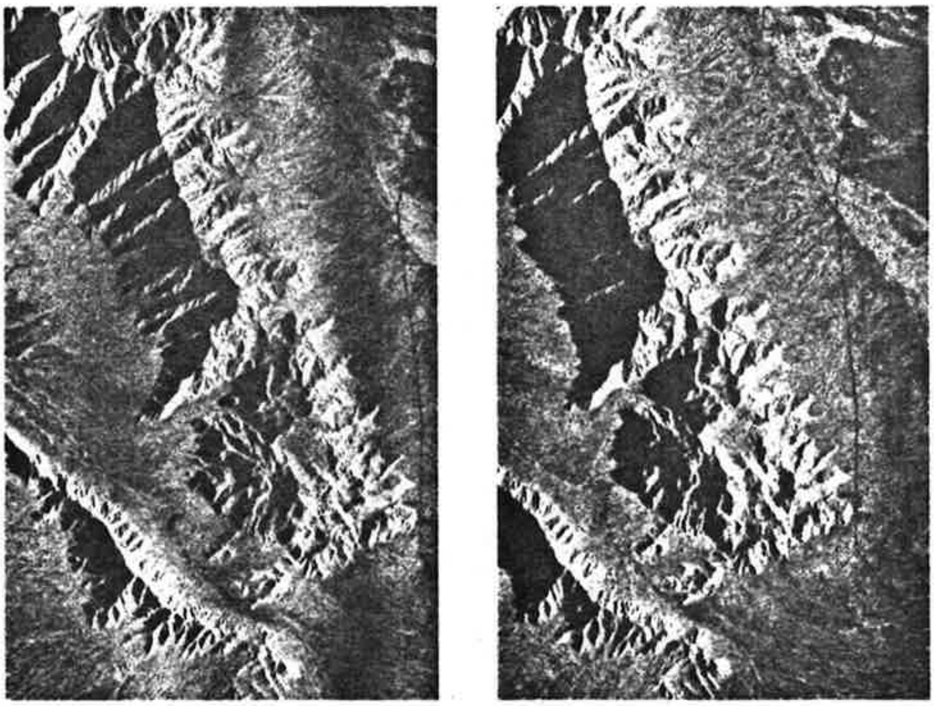

Figure 9. Aircaft stereo radar image pair, same side geometry. X-band, 12 km altitude; Estrella Mountains, Arizona (Courtesy of Aeroservice, Goodyear)

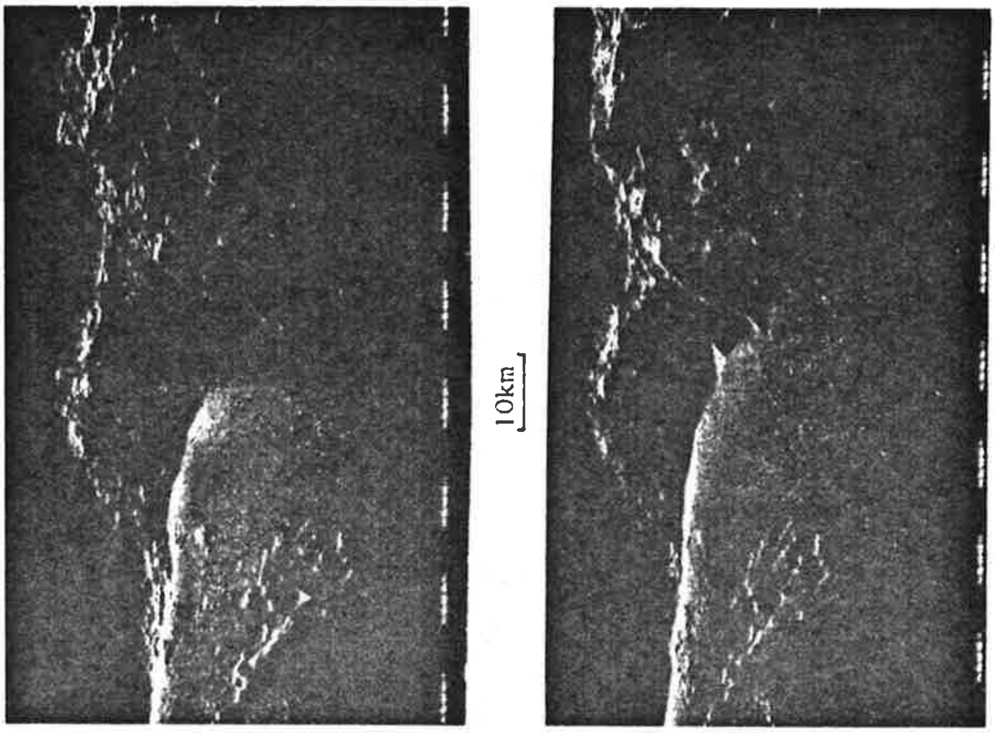

Figure 10. Satellite stereo radar, same side imaging Apollo 17 — ALSE-VHF, Apennine Region on Moon.

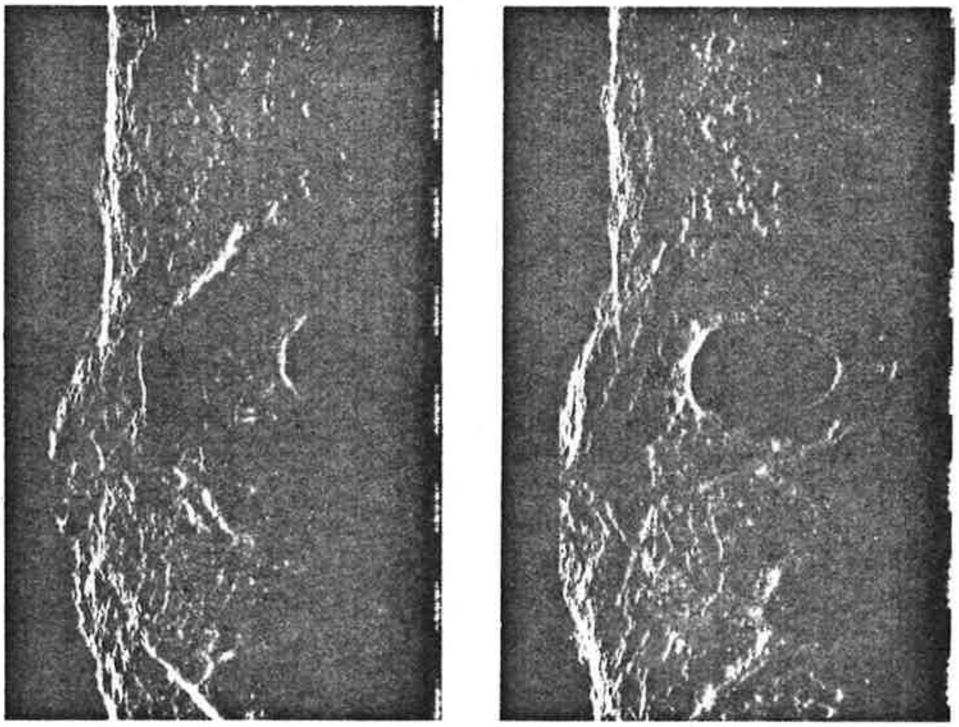

Figure 11. Satellite stereo radar, same side imaging, Apollo 17 — ALSE-VHF, Oriental Region on Moon.

model. One finds oneself in a tradeoff between stereo viewability and mapping accuracy.

B. Stereo Computation

Proper radar stereo computations may start from Equations (1) and (2), where vector $\underline{p}$ is the unknown and to be found from:

$$\begin{aligned} \underline{p} &= \underline{s}' + \underline{A}'\underline{r}' \\ \underline{p} &= \underline{s}'' + \underline{A}''\underline{r}'' \end{aligned} \tag{3}$$

where (') denotes the left and (") the right image.

A simplified formulation is obtained when one assumes a stereo pair with parallel, perfectly straight and level flight lines. Figure 12 shows that in a ground range presentation a stereo parallax Δp can be found that relates to ΔH as follows:

$$\begin{aligned} \Delta H &= p'/\tan\Omega' \\ \Delta H &= p''/\tan\Omega'' \\ \Delta p &= p' \pm p'' = \Delta H(\tan\Omega' \pm \tan\Omega'') \\ \Delta H &= \Delta p/(\tan\Omega' \mp \tan\Omega'') \end{aligned} \tag{4}$$

Equation (4) is valid only if the projection circles can be approximated by straight lines (Figure 12). The plus sign applies to opposite side stereo, the minus sign to same side.

The situation for slant range geometry is slightly more complex. Even a flat ground will appear to be bowed in the radar stereo model. A discussion of this can be found in Leberl (1978, 1979).

C. Accuracies

As with single image mapping, the range of accuracies achieved so far with stereo radar is also diverse. Also here a large series of factors is of influence.

Figure 13 illustrates height accuracies obtained in the past. A conclusion may be that accuracies range from the resolution up to many tens of times the resolution in this regard. Stereo arrangement and control density are the main factors of influence. A study by Gracie et al. (1970) concluded that stereo height measurements would be accurate to within ±13 m. However, this result applies to a density of 35 control points per 100 sq km and very well identifiable test points. Dowideit (1977) achieved a ±25-m root mean square height error using triple overlaps and high density of control. The computing effort was considerable. With a more modest (and realistic) density of control that corresponds to a reconnaissance-type, large area survey, say 4 points per 10,000 sq km , height accuracies may deteriorate to ±100 to ±200 m and more (see, for example, Derenyi, 1975; Leberl, 1977a).

The future can bring about an improved radar stereo capability from aircraft sensors if navigation and resolution improve, and from satellite sensors if look angles are varied sufficiently from one pass to the overlapping one over a given

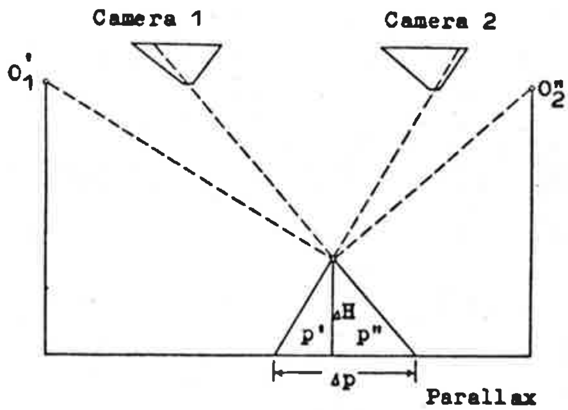

Figure 12. Definitions for the simple stereo computation with side-looking radar. The stereo base 01 02 of radar corresponds to a camera base of camera 1 to camera 2 to produce equivalent parallaxes.

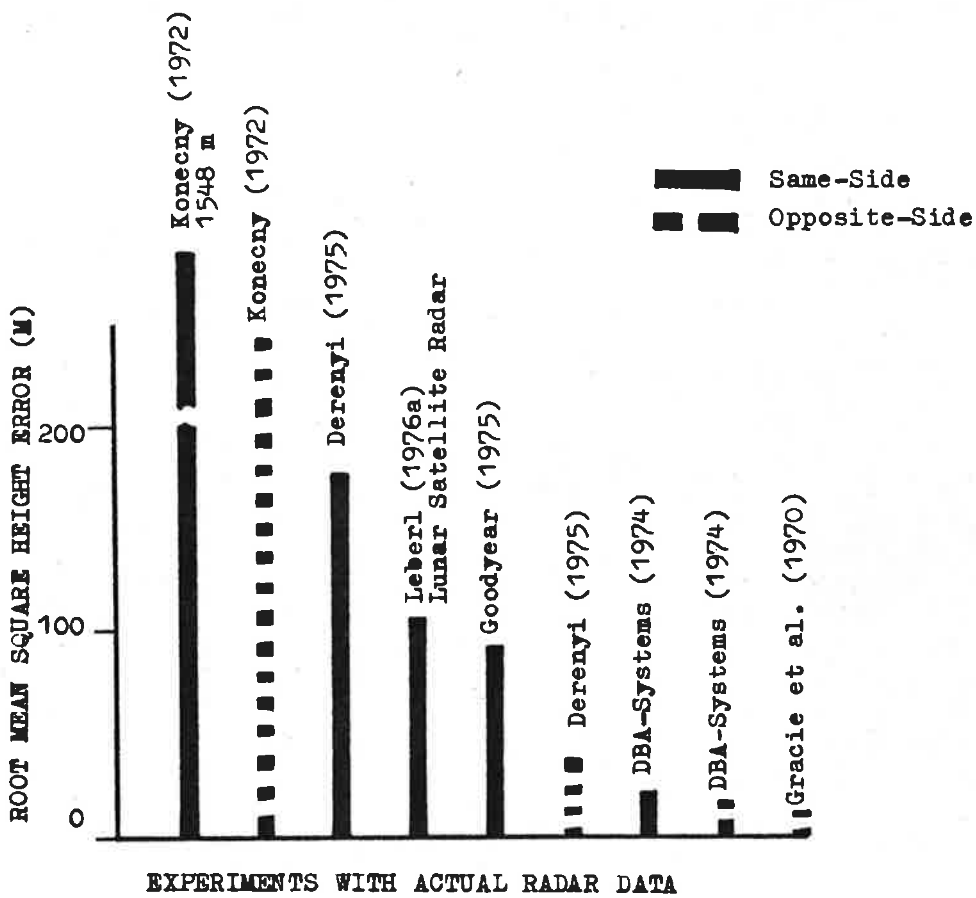

Figure 13. Accuracies achieved in experiments with radar stereo. Results strongly depend on project parameters.

area. However, the active mode of operation causes an inherent weakness of stereo: differing image contents can only be attained if look angles vary, but good visual stereo fusion requires similar look angles.

IV. BLOCK ADJUSTMENT AND MOSAICKING

A. General

Actual radar mapping projects result in blocks of overlapping image strips (Brazil's Radam: 25%, Proradam: 60%, West Virginia, U.S.A.: 25% and 60%). Mapping should thus be based on an adjustment to densify the generally sparse net of control points and to take advantage of the available redundancy in the overlaps. So far radar block adjustment has been applied to planimetry, using the original images (Leberl, 1975c; Leberl et al., 1976b). Three-dimensional radar block adjustment has been studied in a laboratory environment by DBA-Systems (1974) and by Dowideit (1977). The approaches, however, are not practical under present constraints.

Radar mosaicking has been carried out on three levels of sophistication: (a) No control points are used; the images are simply compiled to fit into mosaics. (b) Production strips are flown along parallel lines (for example north-south) and tie-lines are flown across (for example east-west); the tie-lines are controlled by ground control points or by tracking of the aircraft (e.g., Shoran) and the production lines are compiled into mosaics to fit the tie-lines. (c) All production strips are controlled by continuous tracking of the aircraft (Shoran); or a block adjustment is carried out to control all radar images for mosaicking.

Of these the most satisfactory method has been found to be a numerical block adjustment. Settings are obtained for the image correlator (SAR) to correct the scale of the image strips in a recorrelation (Peterson, 1976). Mosaicking is greatly simplified by the method as compared to other approaches.

B. Method of Block Adjustment

1. Internal Adjustment. The block adjustment is based on a fit of the radar image strips with respect to each other using tie-points in the common overlap of images (Figure 14). A coherent image block is obtained as shown in Figure 14 (b). Spline functions are used to describe image corrections Δx (along flight) and Δy (across flight). A spline consists of pieces of polynomials according to Figure 15; each of the pieces is:

$$\begin{aligned} \Delta x &= a_{io} + a_{i1}(x-x_i) + a_{i2}(x-x_i)^2 + a_{i3}(x-x_i)^3, \\ \Delta y &= b_{io} + b_{i1}(x-x_i) + b_{i2}(x-x_i)^2 + b_{i3}(x-x_i)^3, \end{aligned} \tag{5}$$

where a_{ij}, b_{ij} is the jth polynomial coefficient of piece i. The condition applies:

$$x_{i-1} \leq x < x_i \tag{6}$$

which implies that a polynomial piece is valid only in the range delimited by values x_{i-1} and x_i.

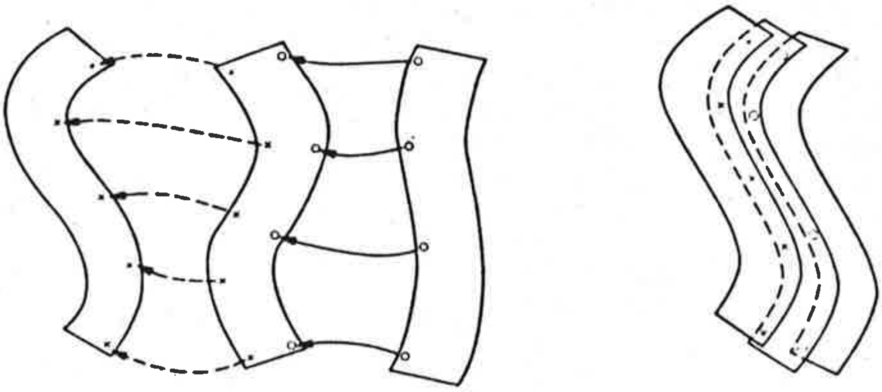

Figure 14. Principle of internal radar block adjustment. Tie-points are used to tie the strips (or stereo models) into a coherent block.

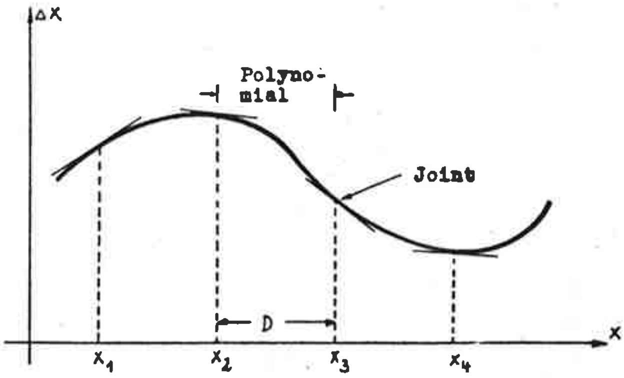

Figure 15. Spline-function or piecewise polynomial. The function is composed of polynomial pieces defined over a range D. Conditions exist at joints that adjacent polynomials are not discontinuous.

Additional conditions apply to enforce a smooth transition from one polynomial piece to the next: the derivatives of 0th, 1st, 2nd order are made identical at the joints of polynomial pieces. We find:

for the function value (0th derivative):

$$a_{io} + a_{i1} \cdot D + a_{i2} \cdot D^2 + a_{i3} \cdot D^3 = a_{i+1,\ o}, \qquad (7)$$

for the tangent (1st derivative):

$$a_{i1} + 2a_{i2} \cdot D + a_{i3} \cdot D^2 = a_{i+1,1}, \qquad (8)$$

for the curvature (2nd derivative):

$$2a_{i2} + 6a_{i3} \cdot D = 2a_{i+1,1}, \qquad (9)$$

D is the length of the polynomial piece:

$$D = x_{i+1} - x_i. \qquad (10)$$

2. <u>External Adjustment</u>. The coherent radar image block must be transformed into the net of ground control points. The principle is illustrated by Figure 16. Any method of interpolation can be used to fit the image block to the control points. Often these methods are denoted by "warping" functions or "rubber sheet stretching."

Internal and external adjustment can be carried out sequentially or simultaneously. A sequential solution has the advantage of low programming and computational efforts. The generally limited density of ground control and dominating effect of periodical ("systematic") image errors permit the conclusion that a sequential solution does not produce results significantly inferior to a simultaneous approach (Leberl, 1975d).

C. Results

Block adjustment accuracy has been evaluated in a controlled experiment with images from the U.S.A. (Leberl, et al., 1976b). The result is shown in Figure 17. The abscissa shows the density of control, the ordinate the root mean square point errors in check points. The image had side-laps of 20%.

An equal distribution of ground control produces the best results. A point density of 15 points per 100,000 sq km can result in rms point errors of about ±150 m (or coordinate errors of ±100 m).

DBA-Systems (1974) and Dowideit (1977), in a more sophisticated, three-dimensional method of computation, obtained results that were about 3 X the resolution of the radar images, using however an unpractically high density of about 10 control points per 100 sq km (10,000 points per 100,000 sq km).

V. APPLICATIONS

The term <u>mapping</u>, as understood by the US Federal Mapping Task Force (Donelson, 1973), comprises

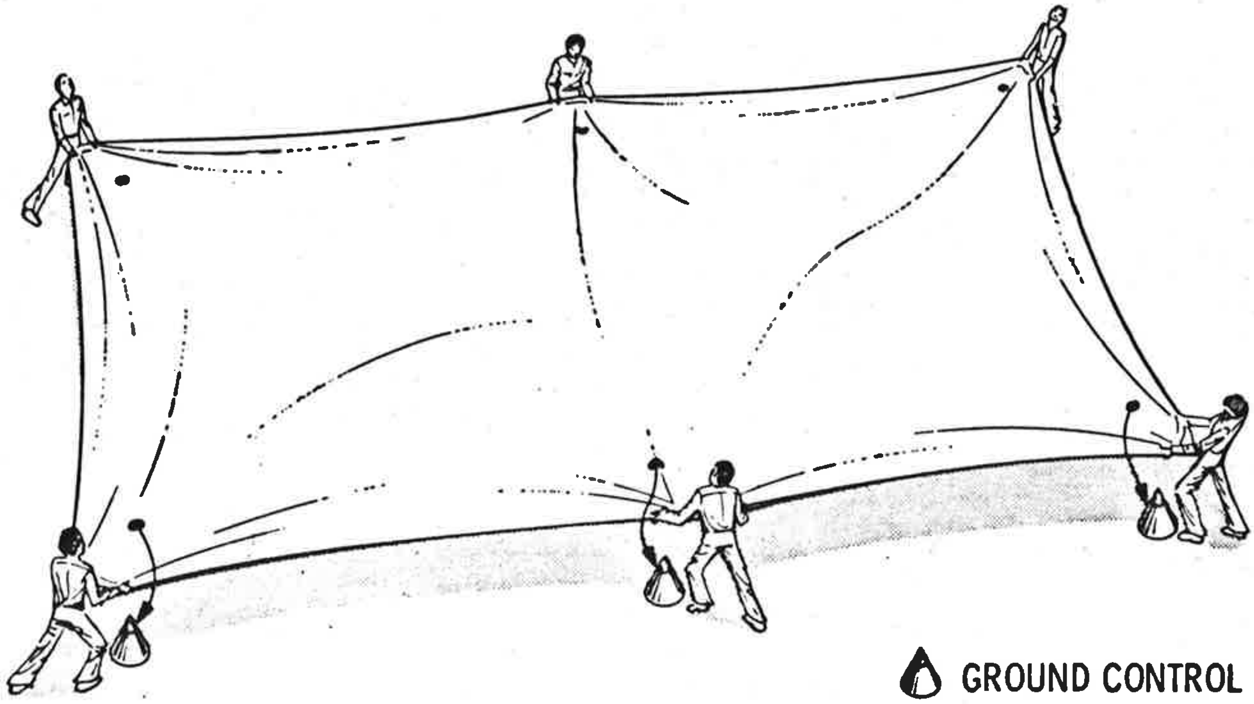

Figure 16. Principle of external radar block adjustment: the coherent block is made to fit the ground control points. Methods of fitting are numerical interpolation ("warping," "rubber sheet stretching").

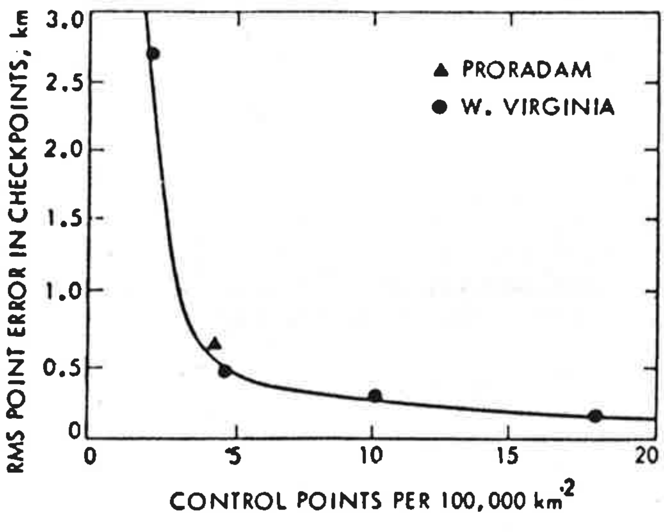

Figure 17. Accuracy of radar block adjustment for mosaicking: data are from an experimental radar block in West-Virginia (Leberl, Jensen and Kaplan, 1976) and from Colombian Proradam (Leberl, 1977a).

Land surveys (point positioning for geodesy, engineering)
Land mapping (plainimetric, topographic, thematic),
Marine mapping (nautical charts, bathymetry, floating aids, hazards)

Instead of focussing on some specific radar mapping applications it may be more relevant to discuss such applications in general terms. For specific applications reference is made to an extensive literature (see Bibliography). From the point of view of point positioning accuracy and of resolution of details, radar is generally no match for current methods of surveying and photogrammetry. However, timeliness and costs of mapping products are often of such an overriding concern that radar's independence from weather and sun illumination could justify a certain spectrum of mapping applications in spite of its limited accuracy performance.

These applications, however, are only in land and marine mapping, not in point positioning tasks. These would be useful only in planetary exploration, such as on Venus, or to support mapping functions such as image rectification.

A. Land Mapping: Planimetry

Table 1 illustrates the map accuracy standards as they apply in the USA.

Table 1. Map accuracy standards in the U.S.A. in meters, expressed for planimetric point positioning

Scale	90% of coord. errors, m Class			Stand. deviation of coord. errors, m Class		
	A	B	C-1	A	B	C-1
1:250,000	90	180	359	54	110	218
1:100,000	36	72	143	22	44	87
1: 50,000	18	36	72	11	22	44

Comparison of this table with radar mapping accuracies clarifies that airborne radar mapping essentially can satisfy scales 1:250,000 at class B-level, or 1:100,000 at class C-1 level. Satellite radar can be expected to have a geometric stability superior to aircraft radar so that the potential exists for mapping errors of only in the order of magnitude of 30 m or so, provided that resolution permits such precise point identification.

B. Land Mapping: Height

For height mapping, stereo radar accuracies are generally not sufficient. Only in the context of thematic mapping (geomorphology, for example), or as a means to rectify individual images, must one see the usefulness of radar stereo. Only under very special circumstances, such as on Venus, or in arctic areas, may one find radar a tool suitable for measuring heights. However, space photography such as the large format camera on the Space Shuttle, on Space Lab and later on a free-flying Multi-Mission Modular Spacecraft (MMS) must be expected to be superior in height accuracy.

C. Thematic Mapping

Radargrammetry is an obvious tool for preprocessing radar images for subsequent thematic analysis. Applications include merging of multitemporal data of images from different sensors and of images with maps or with topographic relief data. An example is the radar-Landsat synergism (Harris and Graham, 1976, Daily et al., 1978).

D. Marine Mapping

Nautical charts exist at the following scales in the U.S.A.:

Type	Scale Range
Sailing	< 1:600,000
General	1:100,000 to 1:600,000
Coastal	1: 50,000 to 1:100,000
Harbor	1: 50,000

Many inhospitable areas of the world with low illumination levels (polar regions) and/or cloud covers must still be served in the need for charts. Man-made point features such as ships and floating aids and nautical features such as icebergs and sea-ice can well be mapped by radar (Super and Osmer, 1975; Leberl et al., 1979). This is of particular significance because of the relative ease with which it is possible to signalize all image features on an otherwise specularly reflecting water-surface.

VI. RECOMMENDATIONS

Radargrammetry still is lacking significant efforts for technique development and for experimental performance verification. Methods of rectification of single images, stereo mapping and use of blocks of overlapping image strips must be studied to more fully understand the applicability, possibilities, and limitations of radar mapping. Investigations must include development of efficient techniques to employ modern mapping equipment such as differential rectifiers, analytical photogrammetric plotters, and digital image processing systems.

Concepts and questions can be treated using aircraft data. Such data may be of great value for themselves and for qualitative evaluation of expected results from satellite radar. They may be misleading, however, concerning quantitative conclusions on satellite radar; as a result one should use aircraft data in an initial phase of work to delimit, in general terms, the potentials of satellite radargrammetry and following such experiments with data from space. Short space missions such as those with the Space Shuttle could prove to be of singular importance to test and verify various concepts and expectations concerning merging of radar with digital terrain height files and other images, stereo mapping and point positioning for rectification using orbit data, and control points and overlapping image strips. During an experimental phase, extended space missions would not add significantly beyond the configuration that is available from short sorties.

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