SIDE-LOOKING RADAR IMAGE OF ARCTIC SEA ICE

IMAGING RADAR APPLICATIONS TO MAPPING AND CHARTING

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ABSTRACT

   The present paper will review past and present radar mapping achievements
and examine tasks and prospects of radargrammetry. The radar mosaic at scales
1:100 000 to 1:400 000 is thus far the typical radar mapping product applied to
vast areas in excess of 10 million square kilometers, mainly in Latin America,
the U.S., Indonesia, the Philippines and Australia. During the past several
years it has been learned that aircraft radar permits mapping of extensive areas
with a planimetric accuracy of about ±100 m, and in exceptional cases, of
about ±20 m. For stereo-radargrammetric height accuracy, also about ±20 m was
found to be feasible. Radar mapping has presently become possible from space-
craft. Up to now, orbital radar images have only been produced for lunar
exploration. An Earth resources imaging satellite radar will orbit our planet
as part of the SEASAT experiment from 1978 onwards. It is thus possible that
radar images might in the future be applied to a dramatically greater extent
than in the past to mapping tasks for which timeliness and economy are of over-
riding concern.

RESUME

   Cette contribution passe en revue les réalisations passées et présentes du
radar en cartographie et examine les applications de la radargrammétrie. Des
mosaiques d'images radar à l'échelle de 1:100 000 à 1:400 000 sont typiques
pour l'utilisation du radar.   Jusqu'à présent des surfaces de plus de 10
million de kilomètres carrés, principalement en Amérique Latine, et aussi en
Indonésie, aux Philippines et en Australie, ont été cartographiées par radar.
Pendant les dernières années, il a été établi qu'un radar utilisé à partir d'un
avion permet de cartographier de large surfaces avec une précision planimétrique
d'environ ±100 m, et dans des cas speciaux même avec une précision d'à peu près
20 m. La méthode stéréoradargrammétrique permet de mesurer la dimension verti-
cale d'un object avec une précision qui peut approcher ±20 m. Ces dernières
années ont aussi vu le développement de radar à partir d'un vaisseau spatial.
Jusqu'à présent, des images n'existent que de la surface lunaire. Mais un
satellite terrestre possédant un radar à ouverture synthétique sera lancé en
1978 dans le cadre de la mission SEASAT. Il apparait donc possible que des
images radar pourront être utilisées plus que dans le passé pour des problèmes
de cartographie pour lesquels le temps et l'économie sont des facteurs impor-
tants.

ZUSAMMENFASSUNG

   Die vorliegende Arbeit gibt eine Übersicht über Radarkartierprojekte und
radargrammetrische Studien der letzten Jahre. Kartierungsanwendungen von Seit=
wärtsradar betreffen im wesentlichen die Herstellung von Radarmosaiken in den
Masstäben von 1:100 000 bis 1:400 000. Weite Gebiete im Ausmass von mehr als
10 Millionen Quadratkilometern wurden in Lateinamerika, den Vereinigten Staaten,
Indonesien, den Philippinen und Australien bisher kartiert. Radargrammetrische
Arbeiten der letzten Jahre ergaben, dass die Kartierung mittels Flugzeugradar
mit mittleren Fehlern von etwa ±20 m und mehr, und im Falle von Bildmosaiken
mit ±130 m und mehr möglich ist. Satellitenradaraufnahmen wurden bisher nur
während der Apollo 17 Mission zum Mond erzeugt. Aber im Rahmen des SEASAT-
Experimentes werden ab 1978 auch Satellitenradarbilder der Erde aufgenommen
werden. Es ist also denkbar, dass die Zukunft eine Intensivierung der Radaran=
wendungen für jene Kartierungszwecke bringen wird, in denen die Wirtschaftlich=
keit und zeitgerechte Erstellung der Karte Vorrang vor anderen Anforderungen
haben.

Frontispiece: Arctic ice floes imaged on 18 august 1975 by JPL's L-band
synthetic aperture radar system; images were taken during a mission for
the Arctic Ice Dynamics Joint Experiment (AIDJEX). Image scale: ⊢__3km__⊣

1. INTRODUCTION

The period since 1972 was marked with a steady increase of the use of SLR imagery particularly for reconnaissance type mapping at small scales (1:100 000 and smaller). Military security restrictions on radar resolution, and on radar studies, were largely dropped, so that at present radar data are available for civilian purposes with a ground resolution of 3 x 3m^2. The advent of orbital SLR also fell in the period since 1972. Further momentum has been gained by geo-science SLR due to increased efforts by the U.S. National Aeronautics and Space Administration (NASA) to prepare for Earth orbiting satellite radars to become available in the near future.

Radargrammetric studies have been performed addressing all three of the basic units of photogrammetry, namely the single image, the single stereo-model, and the block of overlapping imagery. However, many studies concentrated on the single image. The intensity of work was less for stereo analysis and least in block-adjustment. Most of these studies could be based on actually available radar imagery. The pre-1972 tendency persisted, however, to employ only very small samples of real data and to study them in an environment and under assumptions that are remote from a production situation.

The present paper attempts to outline the major actual and potential radar mapping applications, to give an account of the present state of satellite radar imaging, and review the radargrammetric work that has been performed since 1972. This review will address separately the single radar image, the radar stereo model and the radar block.

2. RADAR MAPPING APPLICATIONS

2.1 Actual Applications:

By far the most prominent operational imaging radar application is to planimetric reconnaissance-type mapping of cloud infested remote areas at 1:100 000 and smaller. Vast areas of the world have been mapped in this way; the majority of these efforts have taken place since 1972. Although Brazil had begun its extensive Radar Mapping of the Amazon -- RADAM -- in 1971 (Azevedo, 1971; Moreira, 1973), it only recently (and in spite of available LANDSAT-MSS coverage) completed the acquisition of images of its entire territory of 9 million km^2. All Latin-American countries sharing the Amazon Basin have now obtained radar coverage of this area. In addition, Peru mapped a large portion of the Andes by radar, Colombia its Pacific Coast and Nicaragua its entire territory. Other mapping projects include portions of the Philippines, Indonesia, New Guinea and Australia. On most of these projects, there exists no generally available published documentation.

Projects with a near-operational character and a radargrammetric element concerned the application of radar to the mapping of lake ice distribution (Super et al., 1975) and to the tracking of icebergs (Schertler et al., 1975). Sea ice mapping with radar seems only to have been developed to a near-operational status in the U.S.S.R. (Glushkov et al., 1972).

A series of other operational radar applications have thus far not employed radargrammetric techniques. It seems that radar images are being acquired by oil and mineral exploration companies for the study of regional geological fracture patterns and stream network analysis and for the selection of sites for dams and nuclear power plants. However, the compilation of image mosaics is generally without control.

2.2 Potential Applications:

Radar has potential applications in a number of geoscience fields, for which radargrammetry would be at least as much a supporting tool as photogrammetry presently is in the use of metric photography. A major radargrammetric element would occur if future potential applications required the merging of image data from various sensors and times. Attempts to merge data from different sensors are presently being undertaken (Harris and Graham, 1976). No specific conclusions have been reached as to a geoscience application of such techniques. However, there seems to be a growing awareness among remote sensing specialists that (a) ultimately remote-sensor data from many sources have to be combined for optimum interpretability; (b) the detection of changes from sequential imagery will have to consider thoroughly metric aspects of the images; and (c) the topography of the mapped terrain is of such importance to the energy-matter interaction that the (digital) terrain model (DTM) might ultimately find a remote-sensing application in addition to its mapping and civil engineering application.

Radar could be of potential use in the revision of small scale maps. At the present time this potential is, however, entirely unexplored.

A potentially major future task, particularly of satellite radar, may consist of mapping the polar ice motion (ice dynamics). Although charting the distribution of icebergs, lake and sea ice (see frontispiece) for ship navigation has reached a near operational status, mapping of the motion of the polar ice still requires considerable efforts (Leberl, Farr et al., 1976).

3. SATELLITE RADAR

The first satellite radar images were produced in the Apollo Lunar Sounder Experiment (ALSE) during the Apollo 17 mission to the Moon (Phillipps et al., 1973); an example is shown in Figure 1. Radargrammetric studies were carried out with single images (Tiernan et al., 1976), and with a stereo model (Leberl, 1975e, 1976a).
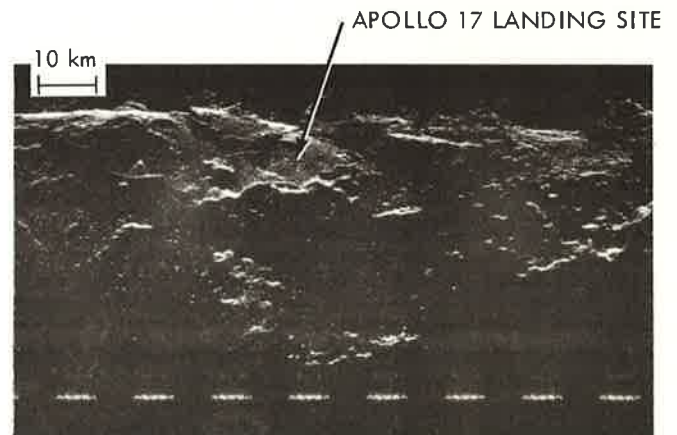

APOLLO 17 LANDING SITE

10 km

Figure 1
Example of orbital side-looking radar image produced during the Apollo 17 mission to the Moon. Image taken with ALSE-VHF (2 m wavelength) synthetic aperture radar

The first Earth orbiting satellite to carry an imaging radar system will be SEASAT, scheduled for launch in 1978. Its main purpose will be to image the oceans, polar ice and coastal areas of North America. Unlike LANDSAT it will not be aimed at imaging the entire world. The image data will be received through modified LANDSAT - ground stations. The additional equipment to do so will require sizeable expenditures (several Mill. U.S. $). However, the U.S. National Aeronautics and Space Administration (NASA) might be in a position to have portable versions of the SEASAT radar receiving equipment made available temporarily.

Table 1
Radargrammetrically relevant parameters of the SEASAT-satellite imaging radar system

Launch	May 1978 (scheduled)
Orbit altitude	790 – 820 km
Orbit inclination	108° retrograde
Orbit period	100 minutes
Radar wavelength	25 cm (L-band)
Elevation angles of line of sight	16.9° – 23.1°
Swath width	100 km
Resolution along track	7 m (25 m)*
Resolution across track in slant range in ground range	8 m 25 m
Dynamic range	50 db
Transmitted radar image data received by modified LANDSAT stations	
Recording of received data probably on magnetic tape	
Map film generation by optical or digital correlation	

*The 7 m resolution will in most radar presentations be artificially degraded to 25 m to achieve equal resolution along and across track and to smooth the graininess of the original data (multi-look mode of presentation)

Other satellite imaging radar projects which presently are only in a planning stage concern the exploration of the planet Venus (Rose and Friedman, 1974) and multifrequency radar images of the Earth to be produced on board the Space Shuttle (Cohen et al., 1975).

Table 1 summarizes those parameters of the SEASAT imaging radar that are of radargrammetric relevance. Differences between airborne and satellite imaging radar do not concern the principle of operation of the sensor, nor are there differences in resolution, swath width or scale. Essential differences relate only to the "look-angles" or elevation angles of the line of sight, consideration of the planetary curvature and various effects of orbit parameters. With airborne radar, elevation angles are normally rather large and vary greatly within a swath, e.g., from 40° (near range) to 80° (far range). In a satellite radar at a great orbital altitude, the horizon and energy requirements limit the elevation angles to comparatively small values, and the variation of the angles from near to far range is rather small (see for example SEASAT, Table 1). This permits image acquisition under almost constant look angles as opposed to airborne radar, and might enhance the value of the resulting imagery for geoscience applications.

4. REVIEW OF PROJECTION EQUATIONS FOR REAL- AND SYNTHETIC- APERTURE RADAR

The basic radar imaging and projection equations have been derived on many occasions in the past (for example: Konecny and Derenyi, 1966; Akowetzki, 1968; Derenyi, 1970; Gracie, et al., 1970; Hockeborn, 1971; Leberl, 1970; Norvelle, 1972; Greve and Cooney, 1974; DBA-Systems, 1974). They were well-established prior to 1972. However, it might be of value to specifically review the differences which exist in the projection equations for radar with real and with synthetic aperture; synthetic aperture radars have become of growing importance during the last few years and are the only system to be made use of from satellites.

Irrespective of the type of side-looking radar imagery, the basic measurement to work with is the slant range r_p between the antenna and point P, and time of imaging, t_p. These entities are obtained in a simple process from measurements in the photographic radar record (see for example, Konecny and Derenyi, 1966; Rydstrom, 1968; Leberl, 1972a). The basic radargrammetric difference between real and synthetic aperture radar is the following: for real apertures, all points imaged at time t lie on a surface whose orientation is defined by the _attitude of the real antenna_; for synthetic apertures, the orientation of the imaging surface is determined by the _velocity vector of the real antenna_.

The position of the radarsensor is denoted by a vector[#] $\underline{s}(t)=(x_s(t),y_s(t),z_s(t))$; the sensorposition is a function of time t. The velocity vector of the antenna is the first derivative of $\underline{s}(t)$ with respect to time t and denoted by $\underline{\dot{s}}(t)=(\dot{x}_s(t),\dot{y}_s(t),\dot{z}_s(t))$. The antenna attitude, finally, is determined by the three classical orientation angles of photogrammetry: $\phi(t)$, $\omega(t)$, $\kappa(t)$. In the following, the time dependency will not be explicitly indicated, so that $\underline{s}=\underline{s}(t),\underline{\dot{s}}=\underline{\dot{s}}(t)$, etc.

A formulation for the projection equation of side-looking radar is now (Figure 2a,b):

$$\underline{p} = \underline{s} + \underline{r}$$
$$\underline{r} = u_p\underline{u} + v_p\underline{v} + w_p\underline{w} \tag{1}$$

where $\underline{p}$ is the position vector of an imaged point in object space; $\underline{u}$, $\underline{v}$ and $\underline{w}$ are unit vectors defining the rectangular antenna coordinate system; $\underline{r}$ is the range-vector from the antenna to the object point; and the auxiliary vector $\underline{p}^*=(u_p,v_p,w_p)$ describes the location of the object point in the $\underline{u}$, $\underline{v}$, $\underline{w}$ antenna coordinate system (see Figure 2b):

$$u_p = r \sin \tau$$
$$v_p = (\sin^2\Omega - \sin^2\tau)^{\frac{1}{2}}r \tag{2}$$
$$w_p = -\cos \Omega \, r$$

where τ is the "cone-complement angle." Hockeborn (1971) calls τ "squint"; it is also explained by Graham (1975), Leberl (1972a,b; 1975a,b) and discussed in considerable detail by Leberl (1976b).

Equation (1) can be rewritten in a more familiar form as:

[#] Vectors are denoted by underligned lower case letters. The dot product is denoted by ($\cdot$), and the crossproduct by (x). Matrices are underlined upper-case letters.
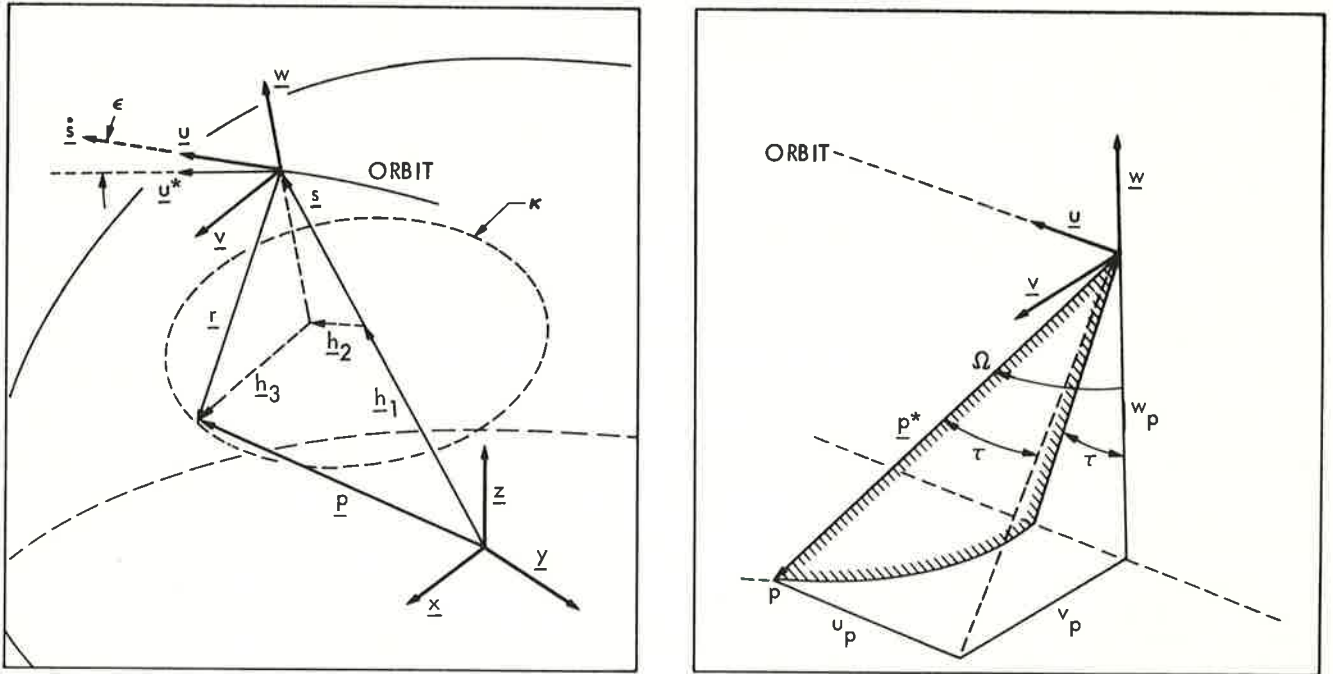
Figure 2: Coordinate systems and definitions for radar projection equations; (a) planetocentric and antenna systems, κ = intersection of range sphere and planetary surface (reference figure); (b) cone complement angle τ and vector $\underline{p}^*$

$$\underline{p} = \underline{s} + \underline{A}\,\underline{p}^* \qquad (3)$$

where the rotation matrix $\underline{A}$ describes the rotation of vectors $\underline{u}$, $\underline{v}$, $\underline{w}$ parallel to $\underline{x}$, $\underline{y}$, $\underline{z}$, so that:

$$\underline{A} = \begin{bmatrix} x_u & y_u & z_u \\ x_v & y_v & z_v \\ x_w & y_w & z_w \end{bmatrix} \qquad (4)$$

For a real aperture radar matrix $\underline{A}$ contains the orientation angles ϕ, ω, κ in their familiar form (see, for example, Leberl, 1972a). For synthetic aperture radar, however, vectors $\underline{u}$, $\underline{v}$ and $\underline{w}$ are functions of the velocity vector $\underline{\dot{s}}$ and position vector $\underline{s}$:

$$\begin{aligned} \underline{u} &= \underline{\dot{s}}/|\underline{\dot{s}}| \\[4pt] \underline{v} &= (\underline{s} \times \underline{\dot{s}})/|\underline{s} \times \underline{\dot{s}}| \\[4pt] \underline{w} &= (\underline{u} \times \underline{v})/|\underline{u} \times \underline{v}| \end{aligned} \qquad (5)$$

Equations (1) or (3) can now be rewritten in several ways, of which the most common (Konecny, 1970, 1972a; Greve and Cooney, 1974; Gracie, et al., 1970, 1972; Leberl, 1971c, 1972a, 1972b; DBA-Systems, 1974) can be given in vector notation as:

$$|\underline{p} - \underline{s}| = r \qquad (6)$$

$$\underline{u} \cdot (\underline{p} - \underline{s}) = \sin\tau \,|\underline{u}|\,|\underline{p} - \underline{s}| \qquad (7)$$

Equation (6) represents a sphere with its center at $\underline{s}$ and radius r ("range-sphere"). Equation (7) represents a cone with the axis along vector $\underline{u}$ ($\underline{u}$ defines the longitudinal axis of the real antenna; or it defines the direction of the velocity vector $\underline{s}$, which in turn is the longitudinal axis of the synthetic antenna). If the radar operation is "normal", then $\tau = 0$ and the cone degenerates

to a plane (the so-called "scanning plane"):

$$\underline{u} \cdot (\underline{p} - \underline{s}) = 0 \qquad (8)$$

For completeness it should be mentioned that the previous equations neglect the small offset $\Delta\,\underline{s}$ between the sensor platform, whose position is defined by $\underline{s}$, and the antenna. It might also be worthwhile to point out that the rotation matrix $\underline{A}$ for real aperture radar might be a composite of several rotations (antenna into antenna mount; antenna mount into sensor platform; sensor platform into reference system).

5. SINGLE IMAGE RADAR MAPPING

Mapping with single radar images has been carried out with the objective to derive object coordinates of imaged points either with or without the use of ground control points; to rectify the radar image for enhanced interpretability or for mosaicking, and to produce a line plot as a cartographic product. The following will address first the mathematical methods of single image radar mapping, and then analyze the accuracy by reviewing the studies that have been carried out on this topic.

5.1 Mapping Methods:

The inputs to single image radargrammetry consist of (a) the measurements of slant range, r_i, and time of imaging, t_i, of a selected number of image points p_i $(i = 1, \ldots i_p)$; (b) the measurements of the sensor-position $\underline{s}(t_j)$, $(j = 1, \ldots j_s)$ and sensor velocity $\underline{\dot{s}}(t_j)$ or attitude $\phi(t_j)$, $\omega(t_j)$, $\kappa(t_j)$; (c) the position vectors g_k of a number of ground control points g_k, $(k = 1, \ldots k_g)$; (d) perhaps a digital terrain model (DTM) of the imaged object.

Computation of the position vector $\underline{p}_i$ of a ground point can be based on either Equations (1) or (6) and (7). The three Equations (1) contain

four unknowns ($p_i = (x_{pi}, y_{pi}, z_{pi})$ and Ω_{pi}); the alternative formulation of Equations (6) and (7) consists of two equations with three unknown (x_{pi}, y_{pi}, z_{pi}). Obviously, one of the unknowns has to be externally measured or given so that the equations can be solved.

In single image radargrammetry, the unknown to be given (or to be assumed to be known) is the height of the object. Two distinct cases can be differentiated: (a) the simplified case, with a straight, level flight parallel to the x-coordinate axis; (b) the general case, with measured flight parameters, in a geocentric coordinate system.

The following will discuss these two cases and then present a method of using ground control points; it will treat the rectification of imagery and the merging of the radar image with digital height data in a process of "digital mono-plotting."

Simplified Case of Coordinate Computation:

Often a simplified flight configuration is assumed for single image radargrammetry (e.g. Rydstrom, 1968; Moore, 1969; Bosman et al., 1971, 1972a, b,; Koopmans, 1974; Hirsch et al., 1976) With a straight, level, and undisturbed flight parallel to the x-coordinate axis the inputs to Equations (1) or (3) simplify to:

$$\underline{s} = (x_s, 0, h) \qquad \underline{\dot{s}} = (\dot{s}, 0, 0)$$

$$\phi = \kappa = 0 \qquad \tau = 0$$

so that

$$x_p = x_s$$
$$y_p = (r^2 - (h - z_p)^2)^{\frac{1}{2}} \qquad (9)$$
$$z_p = z_p$$

General Case of Coordinate Computation:

The position of the sensor is measured by an inertial or similar guidance system, by SHORAN or HIRAN- tracking, or by satellite orbit determination. In all these cases it is convenient to work in a geo-(planeto-)centric coordinate system. The height of the object is in this case expressed as the radius R of the reference spheroid or sphere. According to Leberl (1975 e) one obtains from Figure 2:

$$\underline{p} = \underline{h}_1 + \underline{h}_2 + \underline{h}_3 \qquad (10)$$

where (note that $R = |\underline{p}|$):

$$h_1 = (|\underline{p}|^2 + |\underline{s}|^2 - r^2)/(2|\underline{s}|)$$

$$\underline{h}_1 = h_1 \, \underline{s}/|\underline{s}|$$

$$\underline{u}^* = \underline{v} \times \underline{s}/|\underline{v} \times \underline{s}| \text{ (for } \underline{v}, \text{ see Equ. 5)}$$

$$\cos \epsilon = \underline{u}^* \cdot \underline{\dot{s}}/|\underline{\dot{s}}|$$

$$\underline{h}_2 = \underline{u}^* \left\{ (|\underline{s}| - h_1) \tan\epsilon + r \sin\tau \right\}$$

$$g = (|\underline{s}| - h_1)^2$$

$$\underline{h}_3 = \underline{v} \, (r^2 - |\underline{h}_2|^2 - g)^{\frac{1}{2}}$$

Ground Control Points:

Ground control points can be used in one of two ways: (a) interpolatively (b) parametrically. In the interpolative method, the radargrammetrically computed position vectors $\underline{p}_k$ and the given ground points g_k define difference vectors $\underline{p}_k$ ($k = 1, \ldots k$). These can be used to interpolate corrections in radargrammetric points. Leberl (1971c, 1972a) evaluated a series of different interpolation algorithms with the result that piece-wise polynomials performed best; and Derenyi (1974a) experimentally searched for the optimum polynomial.

An elegant parametric method of using ground control points was formulated by Gracie et al., (1970, 1972) and used by Greve and Cooney, (1974) and Leberl (1975e). This method applies to synthetic aperture radar. According to Figure 3, a plane through the ground point g, but normal to the flight line, is intersected by the flight line. This is represented as a polygon of linear pieces carrying an index ℓ ($\ell = 1, \ldots \ell_s$):

$$e_\ell = \underline{\dot{s}}_\ell \cdot (\underline{s}_\ell - g) \qquad (11)$$

$$\underline{s}_g = \underline{s}_\ell + \underline{\dot{s}}_\ell \, e_\ell / |\underline{\dot{s}}_\ell| \qquad (12)$$

From position vector $\underline{s}_g$, the slant range r_g and time of imaging t_g can easily be determined. The radar image also provides an independent measurement of slant range and time, namely r_p, t_p. The discrepancies $\Delta r = r_p - r_g$ and $\Delta t = t_p - t_g$ can define the coefficients of a correction polynomial for the range and time measurements in the radar image.
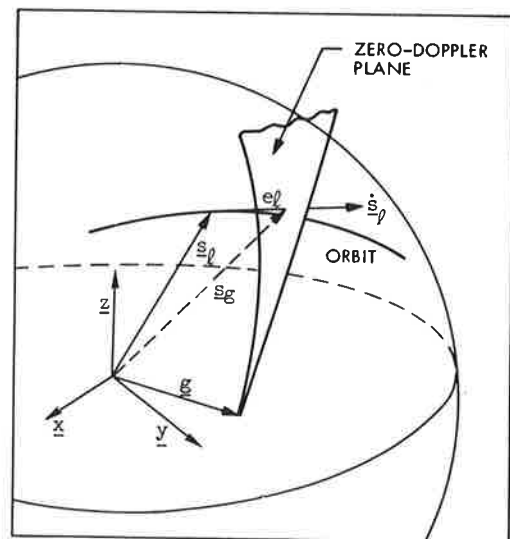
Figure 3

Computation of the radar sensor's orbit position from where ground point g was imaged (single image radar resection)

Rectification:

The along track and across track coordinates of radar images are generated independently of each other. There is, therefore, the possibility of inconsistencies in along- and across-track scales. In the case of synthetic aperture radar images these inconsistencies can, if known, be removed in the process of converting the raw sensor output (the "signal-histories") into the "map film." The method employs a variable scale setting in the

optical correlator (Jensen, 1975; Petersen, 1976). However, there are many more image deformations possible than just those due to a differential scale. Possible sources of such deformations were described by Leberl (1972a), v. Roessel and de Godoy (1974). Methods of rectification are numerical-graphical (Hockeborn, 1971); electro-optical (diCarlo et al., 1968, 1971; Yoritomo, 1972; Masry et al., 1976), or purely digital (Thompson et al., 1972; Leberl, Farr et al., 1976). Other possible concepts have not been realized.

For the *numerical-graphical* method, an ordered set of image-points ("tick-marks") is first transformed into a map system. Square shaped image patches are then rectified graphically using the four surrounding tick-marks and an anamorphic viewer as described by Ambrose (1967).

The *electro-optical* method uses a set of ground control points to compute the empirical relationship between the raw and rectified image. The settings of an electro-optical differential rectifier (Gestalt, Radar Restitutor) are then calculated and the radar image is rectified. In the purely *digital* approach, the radar image is digitized and rectified in a digital image processing routine, using knowledge about systematic corrections and a set of ground control points to determine the coefficients of a "rubbersheet" stretch of the radar image.

Single Image Plotting (Digital Monoplotting):

The method of digital monoplotting is very recent in photogrammetry and has been described and developed for the first time by the Rome Air Development Center (Hall, 1973). It was independently proposed by Makarovič (1973). In this method, relevant image points and lines are digitized off a single image and these digitized data are transformed into a map system using the orientation data of the sensor as well as a digital terrain model (DTM). This method of plotting has been applied to radar imagery by Raytheon (1973) in an operational computer program system (Greve and Cooney, 1974). The program intersects each radar projection circle (Equations (6) and (7)) with the digital terrain surface. This leads to an iterative solution of a non-linear set of equations.

5.2 Mapping Accuracy:

A large number of studies have addressed the question of how accurately the planimetric coordinates of a point can be determined from a single radar image. Generally, those studies rely on the simplified mathematical model of Equation (9) and subsequent correction of the results using ground control points. Table 2 summarizes the radargrammetric accuracies obtained by many different authors employing different radar data. The mere listing of these results can lead to wrong conclusions. Some further specifications are, therefore, in place.

Single image radar mapping is based on assumptions for the surface relief: normally, it is taken to be flat, so that errors occur in those cases where this assumption is not entirely correct. According to Equation (9), such an error Δz_p propagates into the planimetric cross track coordinate

SOURCE	YEAR	ACCURACY (Meters)		RELIEF	CONTROL per 100 km^2	RESOLUTION (Ground -) Meters	ANTENNA		RADAR System Code	SCALE of Images 1:	AREA Designation
		along 1σ	across 1σ				Stabi-lized	Type			Remarks
Gracie	1970	20	14	Flat	10.0	17	yes	synth.	AN-APQ 102		Atlanta, Georgia
Leberl	1971	50	23	Flat	10.0	30	no	real	EMI (U.K.)	200 000	Netherlands
Bosman	1971	47	60	Flat	10.0	30	no	real	EMI (U.K.)	250 000	Netherlands
Konecny	1972	152	255	Mount.		17	yes	real	Westinghouse	216 000	N.Guinee – Conf. Transformation
Greve[*]	1974	35				≥3	yes	synth.	TOPO II	100 000	Dig. Monoplotting
Goodyear	1974	38	30	Flat	3.0	12	yes	synth.	GEMS 1000	400 000	Phoenix, Arizona
Derenyi	1974	89	111	Hills	1.1	17	yes	real	Westinghouse	250 000	Washington D.C.
DBA-Systems[*]	1974	51	26		0.5	3	yes	synth.	AN-ASQ 142	100 000	Radar Interferometer
Konecny	1975	80	79	Flat		12	yes	synth.	GEMS 1000	400 000	Phoenix – Conf. Transformation
Derenyi	1975	30	28	Flat		12	yes	synth.	GEMS 1000	400 000	Phoenix – Control Density not Spec.
Tiernan[**]	1976	209	257	Flat	0.7	30-150	no	synth.	Apollo 17	1 Mill.	Lunar Satellite
Leberl[**]	1976	147	233	Flat	0.3	30-150	no	synth.	Apollo 17	1 Mill.	Lunar Satellite
Hirsch	1976	120		Flat	3.0	30	no	real	EMI (U.K.)	100 000	Netherlands
Leberl	1976	140	190	Flat	0.3	25-150	no	synth.	JPL L-Band	500 000	Alaskan Tundra – Sat. Radar Simul.

Table 2

Mapping accuracies achieved with single image radargrammetry. Resolution data are mostly not accurate and indicate order of magnitude only. Description of relief mostly not available. (*) indicates, that other information besides "radar range" was available. (**) indicates satellite radar.

y_p. Similarly, erroneous slant ranges (Δr) create errors in y_p. One finds:

$$\Delta y_p = (r\ \Delta r - h\ \Delta h)/y_p \qquad (13)$$

so that for standard deviations σ_r and σ_h:

$$\sigma_y^2 = \frac{r^2}{y^2}\sigma_r^2 + \frac{h^2}{y^2}\sigma_h^2 = \frac{\sigma_r^2}{\sin^2\Omega} + \frac{\sigma_h^2}{\tan^2\Omega} \qquad (14)$$

Equation (14) clearly shows how the across-track error reduces for increasing look angles , but increases with the errors of range and height.

The results listed in Table 2 are thus not comparable if they are obtained from imagery taken under different look angles, of terrain with different relief, using different resolutions, or ground points of different identifiability. The orbital radar (Tiernan, 1976; Leberl, 1975e) and the JPL L-band aircraft radar (Leberl, Farr et al.,1976) both employ very steep look angles (elevation angles in orbital radar: $0°$ to $22°$; in JPL aircraft radar: $0°$ to $55°$) so that errors of y are much larger than with systems using larger elevation angles. Also the identifiability of surface features is far inferior on the Moon, or in the Alaskan tundra, to that of man-made features in well-developed areas, where all other results were obtained.

Two accuracy analyses concern specific cases; they are therefore marked by an asterisk (*). The study by DBA-Systems (1974) reports on the planimetric accuracy employing a single radar image and radar interferometer data (for an explanation of the radar interferometer, see: Manual of Photogrammetry (1966)). However, use of the interferometer provides the elevation angle Ω to an object point.

FLIGHT Data	CONTROL per 100 km^2	ACCURACY (Meters)		
		along 1σ	across 1σ	height 1σ
HIRAN	0.0	66.9	23.3	23.3
HIRAN	0.5	57.8	23.3	19.7
None	0.5	51.8	26.6	19.7

Table 3: Mapping accuracy from a single radar image and an interferometer measuring depression angles; AN-ASQ 142 radar system with 3-m resolution used (See DBA-Systems, 1974)

This permits computation of topographic heights even from single images.

For this case, DBA-Systems (1974) obtains results shown in Table 3. It should be mentioned that these results concern geometrically probably the best side-looking radar system ("All Weather Mapping System" with AN/ASQ-142) with well-defined control and check points.

The other study is by Raytheon (1973 ,see also Greve and Cooney, 1974) and employs a digital terrain model (DTM) for digital monoplotting. Consideration of topographic heights should thus reduce the mapping errors.

As a general conclusion, the achieved accuracies vary from better than the radar resolution to several times the range resolution. However, to achieve the sub-resolution accuracy, a very high control point density is required (see Gracie et al., 1970), with, at the same time, the absence of any topographic relief.

6. MAPPING FROM A SINGLE RADAR STEREO MODEL

Far less work has been performed on radar stereo mapping than on single image radargrammetry. However, the methods of stereo mapping and the order of magnitude of what can be expected have been rather well-established, essentially since the 1972 ISP-Congress.

6.1 Mapping Methods - Mathematical Formulations

Radar stereo mapping has limited itself to the purely analytical approach. Only for PPI-radar (non-side-looking) has there ever been the concept for a plotting instrument proposed (Levine, 1963).

Derenyi (1970) and Konecny (1970, 1971) have established that the formation of a stereo model (relative orientation) is not determined for strip imagery. This leads to the conclusion that radar stereo models can only be formed if the elements of exterior orientation are known (measured).

Model formation consists, thus, of the solution of two pairs of equations (Equations (6) and (7)); each pair is obtained from one image of the stereo set, denoted by (') and (") (see Leberl, 1972b, 1975e):

$$\left. \begin{array}{l} |\underline{p} - \underline{s}'| = r'; \quad \underline{u}'\cdot(\underline{p} - \underline{s}') = \sin r\,|\underline{u}'|\,|\underline{p} - \underline{s}'| \\[2mm] |\underline{p} - \underline{s}''| = r''; \quad \underline{u}''\cdot(\underline{p} - \underline{s}'') = \sin r\,|\underline{u}''|\,|\underline{p} - \underline{s}''| \end{array} \right| \quad (15)$$

This is a set of four non-linear equations with three unknowns (x_p, y_p, z_p). Linearization leads to a set of correction equations:

$$\underline{C} \cdot \underline{v}_1 + \underline{D}\Delta\underline{p} + \underline{f}_1 = 0 \qquad (16)$$

where vector $\underline{v}_1$, contains the correction to the 14 observations ($\underline{s}'$, $\underline{s}''$, $\underline{\dot{s}}'$, $\underline{\dot{s}}''$, r', r''); $\Delta\underline{p}$ is the vector of unknown, $\underline{f}_1$ of contradictions; $\underline{C}$ and $\underline{D}$ are coefficient matrices. Solution of this set of equations follows the rules of the method of least squares.

Instead of directly introducing $\underline{s}$, $\underline{\dot{s}}$ as observations into the projection equation, Gracie et al., (1970, 1972) first computed spline polynomials through all observed values of $\underline{s}$, $\underline{\dot{s}}$. The coefficients of the splines were assumed to be constants. Only the time is observed which serves as the parameter of the spline polynomials. This approach thus reduces the number of observations to four (t', t'', r', r''). A completely rigorous approach would however require also the $\underline{s}$, $\underline{\dot{s}}$ to be considered as observations. Such a formulation is used by DBA-Systems (1974) and is also described by Leberl (1976b).

Instead of Equation (15), one can also equate the two sets of Equations (3) (Leberl, 1972b, 1975e):

$$\underline{s}' + \underline{A}'\,(\underline{p}*)' - \underline{s}'' + \underline{A}''\,(\underline{p}*)'' = 0 \qquad (17)$$

This is a set of three equations with the two unknown look angles Ω', Ω''. Linearization leads to:

$$\underline{E}\ \Delta\underline{\Omega} + \underline{f}_2 = \underline{v}_2 \qquad (18)$$

This approach minimizes the distance between the homologue projection circles.

A simplified approach to the formation of a stereo model assumes again, similar to Equation (9), straight and level parallel flights (Derenyi, 1975a, b; Leberl, 1975e):

$$\underline{s}' = (x'_s, 0, h) \qquad \underline{s}'' = (x''_s, B, h)$$

so that

$$x_p = (x'_s + x''_s) / 2$$

$$y_p = (r''^2 - r'^2 - B^2)/2B \tag{19}$$

$$z_p = h - \left\{ (r''^2 - (y_p - B)^2)^{\frac{1}{2}} + (r'^2 - y_p^2)^{\frac{1}{2}} \right\}/2$$

When ground control points are available, then there are again the same two possibilities of interpolative or parametric use of these points as in the single image approach: either the model deformations in control points are used to interpolate corrections in radargrammetric points, or the slant ranges and times of imaging are corrected using Equations (11), (12).

6.2 Mapping Methods – Stereo Configurations:

The normal case of stereo-radargrammetry consists of two parallel flight lines on the same side of the imaged area ("same-side stereo"). Other configurations, e.g. parallel flight lines on opposite sides of the imaged area ("opposite-side"), or at right angles ("cross-wise" – See Graham, 1975b) can create great difficulties in visually perceiving a stereoscopic model , to the point that such configurations cannot be employed.

This exhausts the possibilities for synthetic aperture radar. For real aperture radar, there are still a number of possible stereo configurations, which can be generated along a single flight-line, for example imaging with convergent scanning planes (imaging with ϕ-tilted antennas, Leberl, 1972a); imaging with two κ-swung vertical scanning planes; or the combination of one κ-swung vertical scanning plane with a scanning cone ($r \neq 0$; see Carlson, 1973; Bair and Carlson, 1974,1975). The latter configuration particularly is claimed to provide for a satisfactory visual stereo-effect.

6.3 Mapping Accuracy:

Theoretical studies into the accuracy of a side-looking radar stereo model have been undertaken by Leberl (1972b, 1976b). Expressions for the deformation of a synthetic aperture stereo model were derived by Leberl (1976b). It is shown that for errors pertaining to image ('), one obtains:

$$\Delta x_p = \frac{\Delta x'_s}{2} + \frac{H \tan\Omega'}{2} \Delta y'_s - \frac{H}{2}\Delta z'_s$$

$$\Delta y_p = \frac{\Delta y'_s}{1 - \cot\Omega' \tan\Omega''} + \frac{\Delta z'_s}{\tan\Omega'' - \tan\Omega'} - \frac{\cos\Omega'' \Delta r'}{\sin(\Omega' - \Omega'')} \tag{20}$$

$$\Delta z_p = \frac{\Delta y'_s}{\cot\Omega' - \cot\Omega''} + \frac{\Delta z'_s}{1 - \tan\Omega' \cot\Omega''} + \frac{\sin'' \Delta r'}{\sin(\Omega' - \Omega'')}$$

Equations (20) show clearly, that the model coordinate in flight direction (x_p) is deformed mainly due to errors of the velocity vector ($\Delta\dot{y}_s, \Delta\dot{z}_s$) and that errors in across track direction (y_p) and in height (z_p) are only the results of erroneous sensor positions ($\Delta y_s, \Delta z_s$) and of an error of range r.

Figure 4 gives a graphical representation of Δy_p and Δz_p due to $\Delta r'$ and for specific stereo arrangements. The change-over from a same-side to opposite side configuration represents a singularity of the error curve . It is obvious that small elevation angles Ω', Ω'' lead to small Δz_p errors, but that they inversely create larger Δy_p errors. The opposite is true for large elevation angles.

Experimental stereo analyses have been performed by a number of authors. An overview of the results is given as Table 4. In some cases the
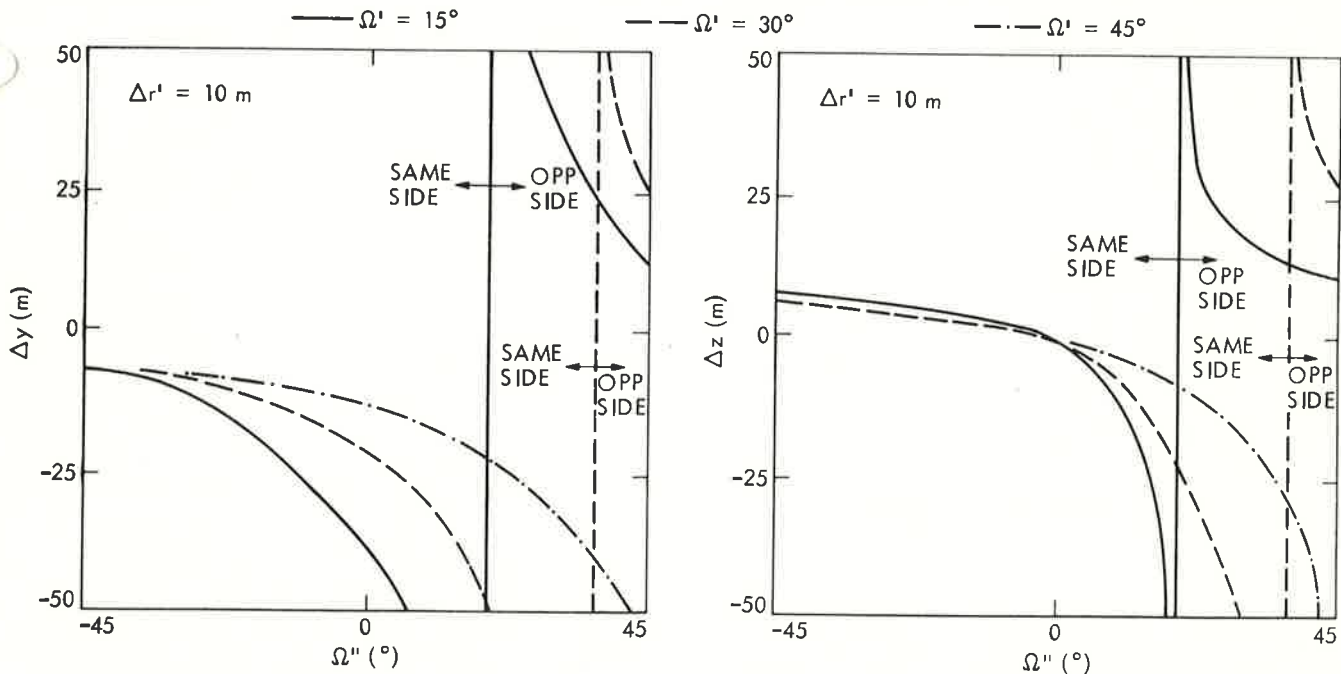

$$——\ \Omega' = 15° \qquad ——\ \Omega' = 30° \qquad —\cdot—\ \Omega' = 45°$$

Figure 4
Examples of error curves for stereo radargrammetry

SOURCE	YEAR	ACCURACY (Meters)			CONTROL per 100 km²	RESOLUTION (Ground -) Meters	ANTENNA		RADAR System Code	REMARKS
		along 1σ	across 1σ	height 1σ			Stabilized	Type		
Gracie	1970	12.2	7.7	13.2	35.0	17	yes	synth.	AN-APQ 102	Opp. Side
Konecny	1972	68.0	138.0	240.0		17	yes	real	Westinghouse	Opp. Side
		130.0	428.0	1548.0						Same Side
DBA-Systems	1974	26.8	21.9	16.7	1.2	3	yes	synth.	AN-ASQ142	Opp. Side
		29.5	25.6	19.7						Same Side
Goodyear	1974			93.0	3.3	12	yes	synth.	GEMS 1000	Same Side
Derenyi	1975			33.0		12	yes	synth.	GEMS 1000	Opp. Side
				177.0						Same Side
Leberl	1975	173.0	510.0	109.0	0.3	30-150	no	synth.	Apollo 17	Same Side - Small Base - Satellite

Table 4

Mapping accuracy achieved by stereo-radargrammetry

accuracies quoted are optimistic, particularly if they concern opposite-side stereo configurations. Opposite-side stereoscopic viewing may be mainly possible in the case of fairly flat terrain or only isolated mountains surrounded by flat terrain. In other cases, lay-over, shadowing, and general differences in the contents of overlapping image pairs may perhaps not permit opposite-side stereo measurements to be taken, although geometrically, the opposite-side stereo arrangement is certainly superior.

The two results marked by an asterisk (*) deserve special comments: Goodyear (1974) measured a single profile of 6 km length and used one control point for "absolute orientation." The results are therefore not really comparable to those of other authors (control density: 1 point per $3 \times 3 \times \pi \approx 30$ km² corresponds to ~ 3 points per 100 km². The other comment pertains to the results of Leberl (1975e) using lunar orbital radar: here, a 2 m radar wavelength, very steep look-angles and not very well identifiable surface features (craters) were employed. As a result, the accuracy achieved had to be somewhat less than in studies with airborne radar. The lunar mapping study provided evidence that the stereo-radar computation according to Equ. (16) is superior to Equ. (18).

6.5 Contouring:

Contouring from radar stereo models has been reported on two occasions: Norvelle (1972) demonstrated the use of the analytical plotter AS-11-A to directly plot contour lines from a deformed radar model. Leberl (1975e) produced a radar contour plot of a lunar feature, however not by directly tracing the countour lines, but by first acquiring a digital height model, from which the contours were interpolated numerically.

7. MAPPING FROM BLOCKS OF OVERLAPPING IMAGERY

7.1 General:

Investigations into the three-dimensional adjustment of a radar block have been reported by DBA-Systems (1974) and Dowideit (1975). A review of methods of sequential and simultaneous adjust-

ment of original radar strips and of independent stereo models has been compiled by Leberl (1976b). However, these studies mainly concern the mathematical and statistical formulation of a solution to the problem. Actual computations concern themselves in the case of Dowideit (1975) with only a single simulated stereo pair, and in the case of DBA-Systems (1974) with a triplet of actual radar images. The modesty of the past efforts in this field could in part be caused by a certain lack of prospective block adjustment applications.

Applications exist, however, for the preparation of base maps for radar mosaicking of large numbers of radar strips. Consequently, a number of results are available on the accuracy of purely planimetric adjustments of radar strips (Leberl 1975c, 1975d; Leberl, Jensen et al., 1976) and on the mere mosaicking of radar images (Lewis and MacDonald, 1970; Berlin, 1971; v. Roessel and de Godoy, 1974).

7.2 Planimetric Adjustment of Overlapping Radar Strips:

Computation of ground coordinates from a block of overlapping side-looking radar images in a process similar to photogrammetric strip adjustment was attempted first by Bosman et al., (1972b) but with a block of only two radar strips. The first adjustment of an extensive block of overlapping radar strips to a set of control points had to be made in the framework of an operational radar mapping project -- PRORADAM of Colombia (Leberl, 1975c). This was followed by a numerical simulation experiment -- as an afterthought to the actual operational task (Leberl, 1975d). Most recently an exceptional block of radar imagery of a well-mapped area in the U.S.A. (W. Virginia) required an operational adjustment, but also permitted an experiment to be carried out to study the performance of several methods (Leberl, Jensen et al., 1976).

The numerical simulation study referred to above (Leberl, 1975d) did show the following: if a radar block is formed by sequential connection of the original radar strips (or stereomodels) whereby spline functions are used to describe image deformations, and if then an external block adjustment, according to Schut (1970), is carried out

then results are obtained that compare favorably with simultaneous planimetric adjustments. The sequential method is very simple, fast and numerically stable. The simultaneous methods are expensive, slow and numerically unstable.

Figure 5 illustrates the results achieved in sequential adjustment of actual radar blocks PRORADAM and West Virginia to sets of ground control points. It appears that with a density of ground control of about 15 points per 100 000 km^2, point accuracies achieved are about ±150 m.
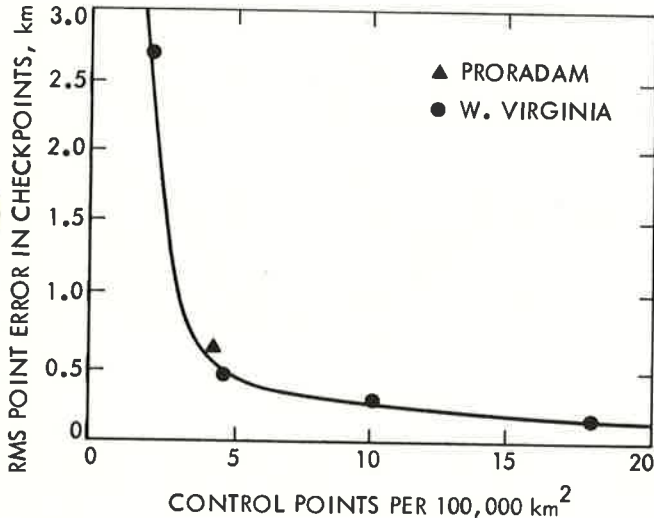
7.3 Mosaicking:

Mosaicking of radar strips can be carried out using the results of the numerical adjustment as a base map. However, the individual radar strips cannot be rectified, except for elimination of scale differences along- and across-track. Therefore, one must expect that mosaicking itself contributes a sizeable mapping error, even if the results of the numerical adjustment were entirely error-free.

In the case of the block West Virginia, check and ground control points were scaled off the mosaics at scale 1:250 000 and off the topographic maps at scale 1:24 000, using in both cases the grids printed on the map sheets. It was found that both groups of points had the same errors of approximately ±200 m. This shows that the mosaicking of largely unrectified radar images added an error that obscures the errors of the numerical adjustment (±130m).

Other methods of mosaicking have been and are in use. A method applied in the initial phase of Brasil's project RADAM is based on complete SHORAN tracking of all mapping flights. An ordered set of image points is then transformed onto a base using the measured aircraft positions and image ground ranges. The images are laid out on this base. This results in mosaics with r.m.s. errors of about ±300 m (v. Roessel and de Godoy, 1974).

In most of the enormous RADAM project of Brazil (9 million km^2), however, not all of the mapping flights were SHORAN controlled: in fact, none of the production flights were controlled, and only a small number of transverse cross-lines (tie-lines) were. Mosaics were laid out using the SHORAN controlled tie-lines as a geometric

reference. This method of mosaicking was estimated by v. Roessel and de Godoy (1974) to lead to errors of the order of magnitude of ±700 m.

It is thus obvious that mosaics based on a numerical planimetric adjustment are more accurate than those resulting from other methods. It can even be expected that the numerical approach is the least expensive one (Leberl, Jensen et al., 1976).

7.4 Three-Dimensional Adjustment of Radar Blocks:

The only 3-D block adjustment with actual radar imagery so far has been reported by DBA-Systems (1974). In this adjustment the flight data are described by spline functions of time t. The coefficients of the splines are solved in the simultaneous adjustment, based on the linearized projection equations (6), (7). Also the measurements of slant range and time are being calibrated in the simultaneous adjustment by postulating an error behaviour according to polynomials:

$$t + v_t = t_o + a_1 r^2 + a_2 r^2 + a_3 r^3$$

$$r + v_r = r_o + b_1 + b_2 r + b_3 r^2$$

(21)

t, r are observations, v_t, v_r are corrections, t_o, r_o are approximations, and a_1, ... b_3 unknown. The program employed by DBA-Systems is thus similarly general as are the well-known photogrammetric bundle adjustment programmes with additional parameters.

CONFIGURATION	CONTROL per 100 km^2	ACCURACY (Meters)			REMARKS
		along 1σ	across 1σ	height 1σ	
Single Image	0.5	51.8	26.6	19.7	Interferometer
Stereo Pair	1.2	26.8	21.9	16.7	Opp. Side
Stereo Pair	1.2	29.5	25.6	19.7	Same Side
Triplet	1.2	18.8	11.4	14.5	Opp. and Same Side

Table 5: Mapping accuracy achieved using single radar image with interferometer and also stereo- and triplet intersections (From DBA-Systems, 1974)

Table 5 reviews the results obtained by DBA (1974) with a block of three radar images. Use was made of interferometer measurements in the single-image approach and of HIRAN tracking of the aircraft.

The very interesting result of Table 5 is that even same-side stereo provides higher accuracy than use of the interferometer in conjunction with a single image. The study by DBA-Systems (1974) also indicated that inclusion of interferometer data in the stereo or triplet intersection does not improve the results.

8. CONCLUSIONS, RECOMMENDATIONS

8.1 Review of Present Status:

The period since 1972 has, for radargrammetry, been marked by the declassification of military know-how (studies and 3 x 3 m^2 resolution imagery), extensive operational reconnaissance type mapping

projects (mainly Latin America), the advent of satellite side-looking radar (Apollo 17 Mission to the Moon; decision for Earth orbital satellite radar in SEASAT) and the continuation of the photogrammetric evaluation of radar images, stereomodels, and radar image blocks.

The development of the U.S. military topographic radar mapping system has been completed. The system consists of hard-and software for production of differentially rectified radar images (using radar interferometer data), digital monoplotting (radar images and digital height model), contour plotting, and control network densification (using the radargrammetric analogy to the photogrammetric bundle adjustment). However, the complete system has not yet been put to extensive tests under near-operational conditions.

Side-looking radar has in its short history (12 years for real-, 6 years for synthetic aperture) mainly found applications to reconnaissance type mapping of vast and remote areas, but not to classical tasks of mapping and charting. The reconnaissance projects aim at producing image maps (mosaics) at scales 1:100 000 and smaller. As a result, radargrammetric investigations have largely concentrated on the methods and accuracy of planimetric mapping from single strips and blocks of radar imagery. Single image mapping accuracies reached up to ±20 m with 10 control points per 100 km^2; and adjustment of blocks of original radar image strips produced an accuracy of ±150 m with 15 control points per 100 000 km^2. Both figures strongly depend on the density of control points available.

Stereoradargrammetric analyses have been performed, particularly in the period since 1972, but only in rather small areas and often not representative of operational environments. Accuracies achieved are up to ±13 m in height, a result that could perhaps not hold up outside the laboratory environment, but that should warrant more attention for stereo radar than has been given in the context of reconnaissance type radar mapping projects.

Radar block adjustment is a field of study that has not attracted the attention of many research workers. The comparatively weak geometry of all dynamic (kinematic) imaging systems does not present great promise for control network densification based on image blocks. However, in the context of reconnaissance type mapping, of image mosaicking for mapping of sea and lake ice, and for future planetary exploration (mapping of planet Venus), radar block adjustment techniques should have valuable applications.

8.2 Recommendations:

Recommendations for future work on radargrammetry should be based on the present trend to view remote sensing as a tool in which various sensors are integrated into one coherent system: each sensor is producing only a specific component of data; but only the integration of all the data from various sources will allow the maximum benefit to be obtained from remote sensing. This particularly will be the case with satellite radar, to be combined with LANDSAT and similar data. In this context, the most significant tasks of radargrammetry are in relating the radar image to other remote sensing data sources. Solution of these problems will call for differential rectification or digital monoplotting, employing perhaps the techniques of digital image processing.

Application of radar to classical mapping tasks have limited themselves to reconnaissance type mapping of remote areas. It is felt that the radar images have not been completely used to their full potential in these projects. It is thus recommended to apply more radargrammetric expertise in radar mapping projects, so that advantage is taken of the information potential of stereo radar.

Apart from reconnaissance type mapping, radar might also have some potential as a tool for map revision. Particularly the advent of satellite radar may suggest exploration of the limits and possibilities of radar for map revision.

Stereo radargrammetric analyses have in the past not dealt with the rather important relationships that exist between physiological limits to perceiving and measuring a radar stereo model and various parameters of the radar configuration and of the imaged area. Such an analysis, while pertinent to stereo radargrammetry, would generate results of significance far outside the mapping community.

New mapping tasks which have not existed in the past but are becoming significant now and can be solved by radar, address the mapping of sea and lake ice, and perhaps of cloud covered planetary surfaces such as Venus. The next few years might see ice mapping as a major radargrammetric task, while planetary exploration by radar images is in the more distant future.

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