1012

Photogrammetric Record, 11(66): 647–665 (October 1985)

MAPPING WITH AIRCRAFT AND SATELLITE RADAR IMAGES

By F. W. LEBERL, G. DOMIK
Vexcel Corporation, Boulder

and M. KOBRICK
Jet Propulsion Laboratory, Pasadena

(Paper read after the Annual General Meeting of the Society on 20th November, 1984)

Abstract

The history of radargrammetry spans about 35 years. It has moved from early plan position indicator (PPI) radar records of 1948 to the current (1984) space shuttle imaging radar SIR-B. We can look forward to the future 1989 European and Japanese remote sensing satellites ERS-1 and NASA's 1988 Venus Radar Mapper (VRM) mission. The mapping application requires that methods be available to deal with single images, stereoscopic pairs or blocks of image strips. The predominantly digital data format suggests that radargrammetric methods should be implemented in digital image processing systems for rectification, digital terrain elevation extraction and multi-image registration for change monitoring. This paper presents a review of current radargrammetric understanding, applications and expected developments.

INTRODUCTION

FIRST REPORTS on the topic of radargrammetry date back to 1948–50 when Rinner (1966) in Austria and Protherse at Ohio State University made original contributions, although the term itself was coined by Levine (1960) at a later date. The main body of radargrammetric theory and analysis concerns side looking radar (SLR) images as they have become available since about 1961. Prior to that, radar images were generated at a much lower geometric resolution by systems called plan position indicators (PPI). While of great value for aircraft and ship navigation, these systems have been entirely superseded by SLR in the context of geoscience and remote sensing.

Radargrammetry deals with the photogrammetric aspects of radar images and is described in a number of survey articles, most recently by Leberl (1983). This review will avoid repetition by focusing on the most recent work, carried out during the reporting period of the International Society for Photogrammetry and Remote Sensing (ISPRS) since 1980. Table I summarises the highlights of recent radargrammetric work and concerns new data, new methods and new applications research. It is evident that a wealth of satellite radar data from the US National Aeronautics and Space Administration (NASA) Seasat and space shuttle missions has become available which dominates most recent US activities in the field; in Europe the SAR-580 campaign has resulted in widely distributed aircraft imagery.

The domain of radargrammetry methods has been enhanced by concepts such as

Table I. Recent highlights of radargrammetric research (ISPRS reporting period 1980–84).

Events	*Results*
Seasat radargrammetric performance evaluation: positioning accuracy	± 20 m at seven control points per 1000 km^2.
Image simulation based on digital elevation models (DEMs)	For stereoscopic viewing studies.
Differential radar image rectification	Radar image time series.
Radiometric radar image rectification	A new image product for interpretation.
Analytical plotter programming for radar stereomapping	DSR-1, APPS-IV, AS-11.
ESA SAR-580 radar image analysis	Height mapping accuracy of ± 7 m.
SIR-A image map superposition and rectification	Calibration of previously uncalibrated radar image brightness.
Seasat arctic sea ice motion measurements	± 300 m accuracy of ice flow positioning over one month.
Radar image interpretability for mapping	Understanding of thematic image content for small scale mapping.
SIR-B radar analysis with variable look angles	Radar derived digital elevation models of ± 90 m accuracy.
Various stereomapping experiments	r.m.s. errors typically about three times the horizontal resolution.
Venus Radar Mapper (VRM) mission definition studies	Mission planning support documents.
Shape from shading using single radar images	The concept of radarclinometry.

to predict optimum stereoscopic radar image pairs and flight arrangements for mapping of geological lineaments.

Applications studies dealt with the available data to determine sea ice motion (Leberl *et al.*, 1983), to interpret manmade features for general purpose mapping (Dowman and Morris, 1982; Konecny *et al.*, 1982), to obtain digital terrain elevations on an analytical plotter (Autometric, 1982; Raggam and Leberl, 1984) and to combine existing DEMs with digital radar images for the creation of rectified ortho-image maps, image time series (Leberl *et al.*, 1981) and tools for thematic interpretation (Domik *et al.*, 1984 a, b, c).

Operational applications of radargrammetry were limited to traditional reconnaissance mapping of vast areas that were previously poorly mapped. Most recently this concerned a commercial radar image block project in Ecuador performed by Aero Service Corporation/Goodyear in 1983 and 1984. It is unclear to what extent the reported routine mapping of sea ice in the territorial waters of the USSR incorporates radargrammetric concepts.

There follows a discussion of recent work performed by the authors. It will review the type of processing that has been applied to analogue and digital radar images of the Seasat and space shuttle flights and from the SAR-580 campaign. This will support the conclusion that considerable radargrammetric technology will need to be developed and applied in complex future environmental monitoring tasks based on multisensor data sets with digital satellite radar images.

Radar Image Simulation

A variety of radar imaging arrangements can be studied in an economic manner, given proper image simulation capabilities. The simulation predicts how an image will present object information. This in turn can provide answers to questions which otherwise might require the acquisition of aircraft or even satellite radar images. Publications on radar simulation focus either on accurate signal prediction from well described scatterers (Holtzman *et al.*, 1978) or on an accurate representation of geometric effects due to topographic relief and platform perturbations (Bair and

Simulation Technique

Input to the image simulation exists as a digital elevation model (DEM), a thematic description of surface properties, a flight path and a set of imaging parameters such as resolution, sweep delay and squint angle. Fig. 1 illustrates an image space algorithm; for each image pixel location, one computes a circle in space as the geometric locus of the object point. The intersection of circle and digital elevation model results in this object point. The image pixel gray value is a function of one of several backscatter laws and of topographic slope, resolution, thematic properties and noise. The definition of the circle in space requires an understanding of radar imaging geometry; the image density assignment relates to an understanding of radiometric properties. Details of the simulation were described in an earlier report by Domik *et al.* (1983).

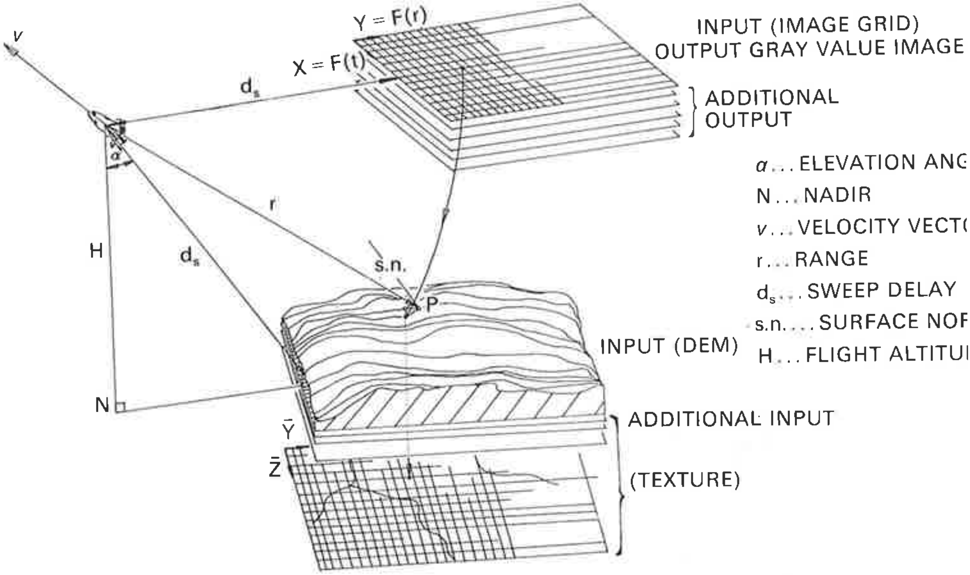


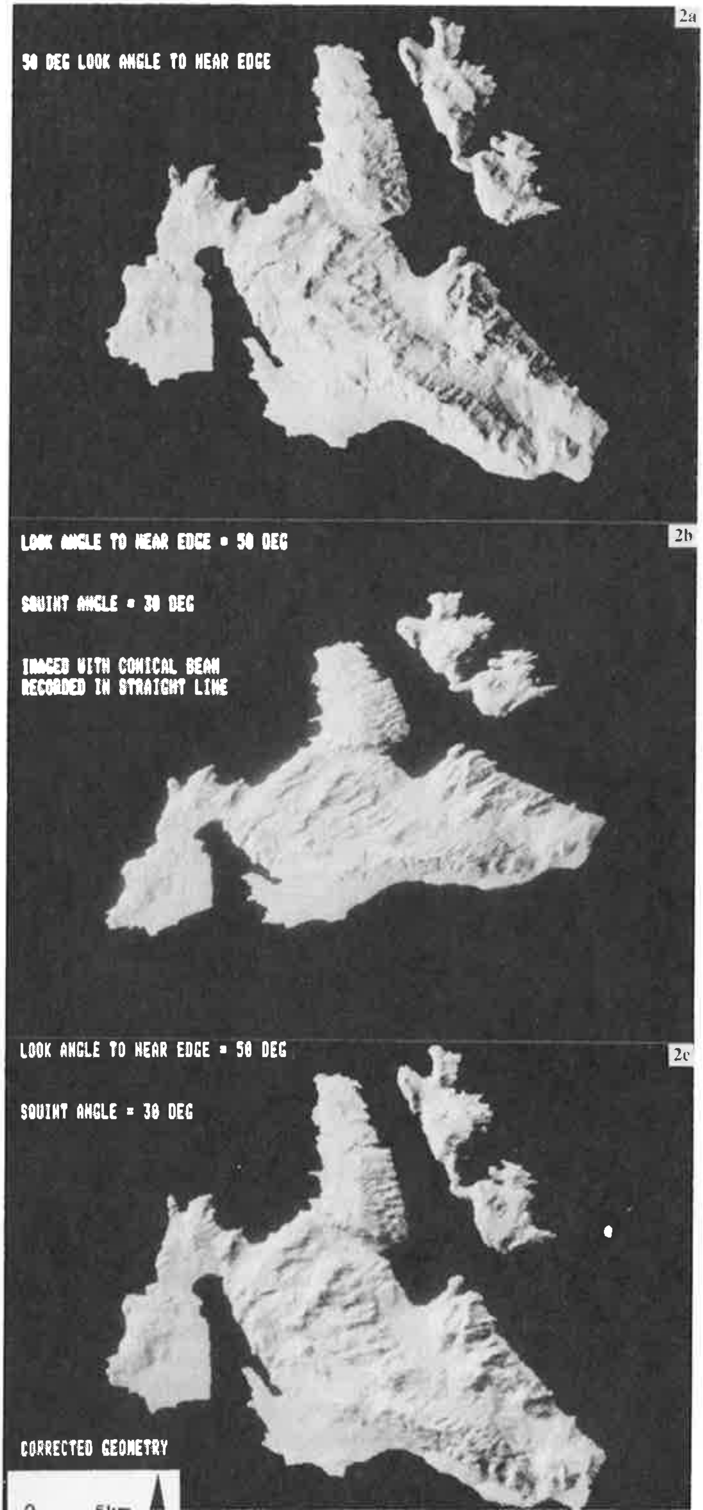
FIG. 1. Image space algorithm.

Radar Parameter Studies

(a) Squint

Fig. 2 is a set of simulated radar images using a DEM of the Greek island of Cephalonia. The squint angle was varied to study the effect on interpretability and on stereoviewing. This case study is of particular interest since actual radar images have never been produced with large squint angles. Simulation, therefore, provides a unique tool to predict image appearance. It is apparent how the image geometry is systematically altered; however, it is shown in Fig. 2(c) that this can easily be rectified since it is an entirely systematic effect, much like the panoramic distortion in scan images.

The significant differences in squinted mode images consist of variations in the illumination direction. As a result, squinted mode images have different brightness/shadow characteristics from unsquinted or (so called) zero-doppler images (compare Fig. 2(a) and (c)). No studies have come to the attention of the authors which would employ or even speculate on the employment of the squint mode in terrain analysis.


2a
50 DEG LOOK ANGLE TO NEAR EDGE
2b
LOOK ANGLE TO NEAR EDGE = 50 DEG
SQUINT ANGLE = 30 DEG
IMAGED WITH CONICAL BEAM
RECORDED IN STRAIGHT LINE
2c
LOOK ANGLE TO NEAR EDGE = 50 DEG
SQUINT ANGLE = 30 DEG
CORRECTED GEOMETRY

(b) Stereoviewing

The concept of side looking radar stereoviewing has been discussed since LaPrade's (1963) work. A lack of available imagery has hampered specific parameter studies. Recently, image simulation has permitted more thorough experimental studies to be done to define the optimum imaging arrangements for good stereoscopic viewing. The examples of Fig. 3 illustrate four imaging look angles of 10°, 50°, 80° and −80°; obviously the opposite side cases cannot be visually merged (any combination with −80°). Same side cases can all be merged, where a 35°/65° or 45°/70° combination is subjectively judged best for ease of viewing and for vertical exaggeration.

This type of study suffers from limitations in the image simulation technique. The input to simulation excludes planimetric features and the resulting image has no noise. Both the noise and the differences in presenting planimetric features may make successful stereoviewing more difficult than it appears from the simulation.

Squinted mode images can be employed for stereoscopic viewing. The maximum squint angles permitted appear to be about 35°. When larger squint angles are used, one cannot fuse the two squinted image pairs due to differences in shadows and brightness.

(c) Look angles

Image simulation based solely on digital slope information is only meaningful in areas which are not flat. Questions on look angles also arise in flat areas in studies of sensitivity to surface roughness or moisture. However, the current simulation system cannot support parameter studies in this context. What it can support is a visual examination of look angles as they affect the interpretation of topographic features such as lineaments. Given a geological setting such as that in Sardinia, Italy, such interpretation is found to be optimal at look angles in excess of 20° off-nadir (Domik *et al.*, 1985).

(d) Flight direction

It is a well established observation that geomorphology and geological lineaments express themselves in different ways on radar images as the flight direction changes. Fig. 4 illustrates this fact. Geological image interpreters have been asking about the number of flight directions required to obtain a complete interpretation of relevant features. Such questions can be addressed *via* simulation; contrary to the predicted optimum of at least two perpendicular flights (MacDonald and Waite, 1971), simulation also shows that two flights at a much smaller variation of direction will suffice. As is shown in a study for the European Space Agency, an angular divergence of 22°·5 is sufficient to present a complete and well identified description of geological linear information (Domik *et al.*, 1985).

Convergent Stereo-imaging

The space shuttle mission with the SIR-A experiment in 1981 produced some overlapping radar images. Stereoscopic parallaxes did not result from parallel flight lines with differing look angles, but from the fact that the two flight lines intersected at various angles. Fig. 5 illustrates the parallax geometry and Fig. 6 presents an overlapping radar image pair.

It is immediately apparent that such an imaging arrangement will not only produce valid x parallaxes parallel to an observer's eye base, but also undesirable y parallaxes at right angles. Fig. 7 is a plot illustrating the x and y parallaxes in the overlap area of Fig. 6. The stereoscopic examination of such overlapping images is only possible as long as

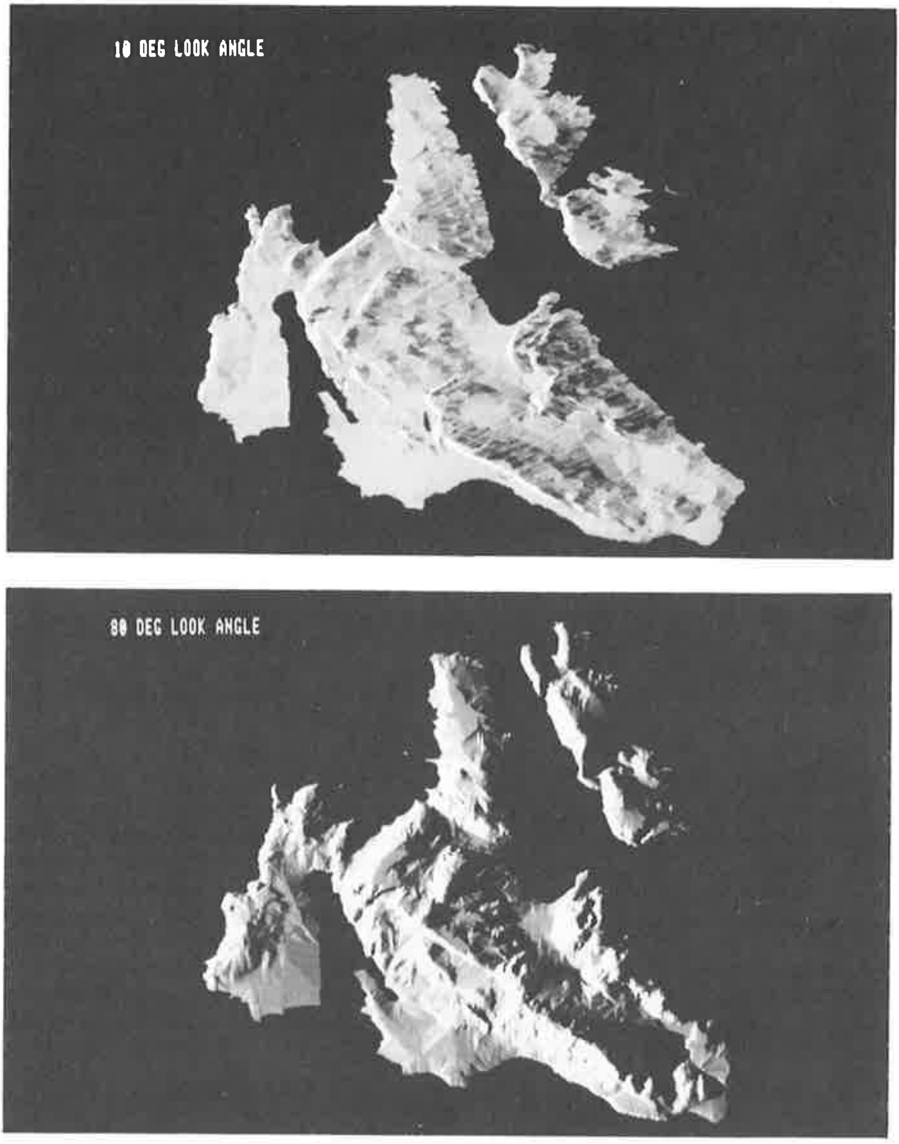
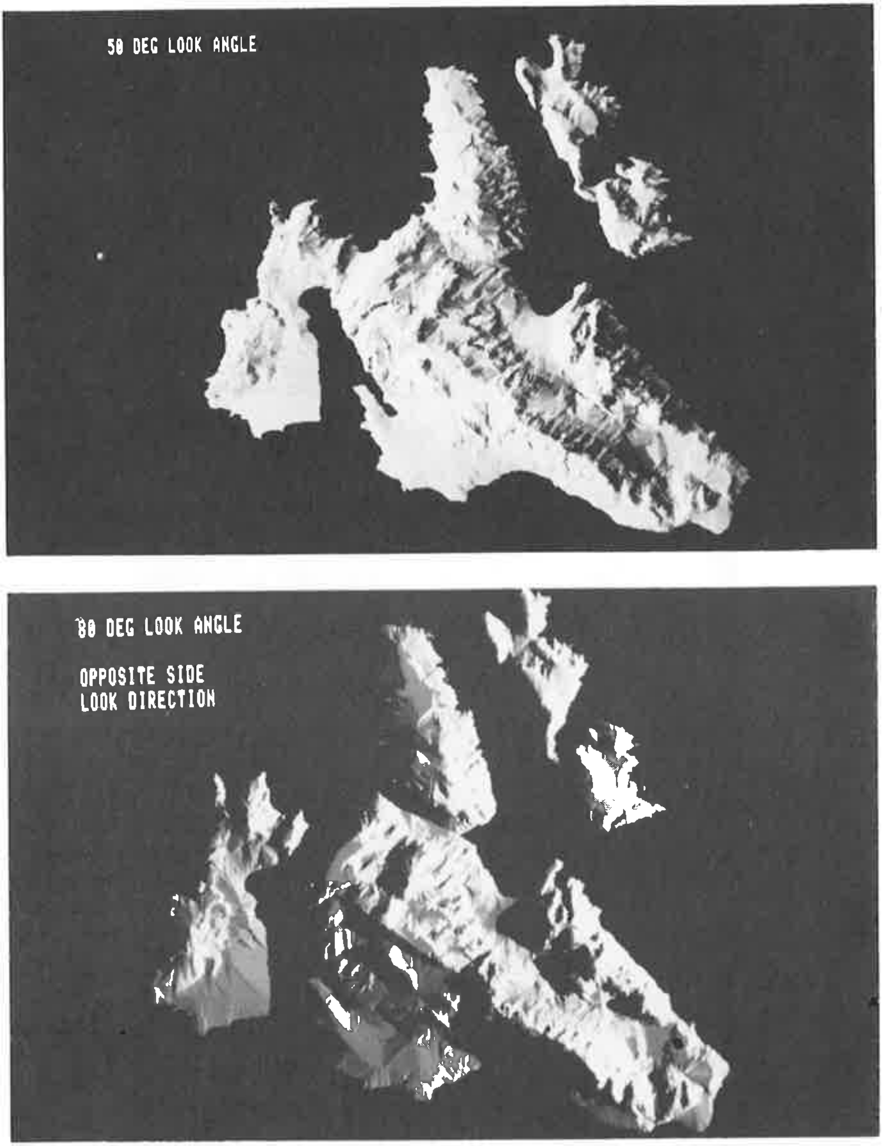


FIG. 3. Simulated set of satellite radar images of Cephalonia, Greece, at

RADAR STEREOMAPPING ON AN ANALYTICAL PLOTTER

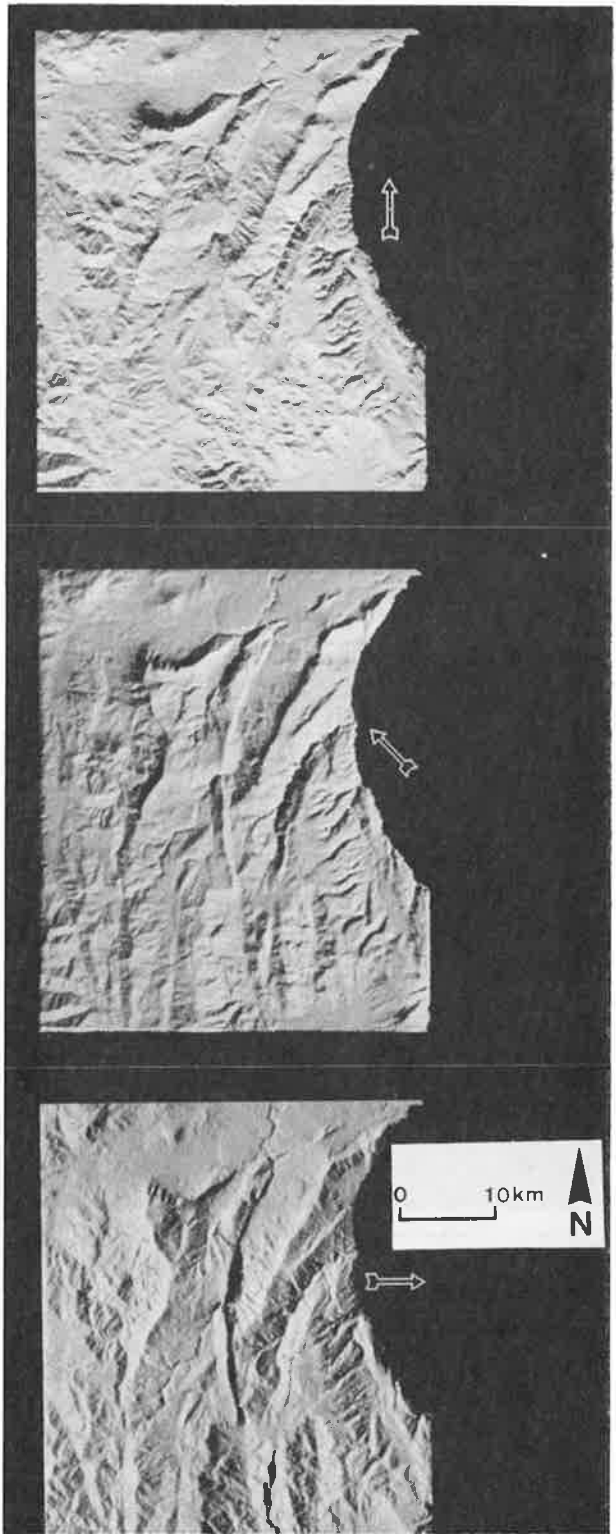
Procedure

Norvelle (1972) was the first to demonstrate the use of an analytical plotter for radar stereomapping. Recent microprocessor based, easily programmable analytical plotters have made the task more manageable. Raggam and Leberl (1984) reported on a system called SMART (*s*tereo*ma*pping with *r*adar *t*echniques) that is implemented on a Kern DSR-1 plotter. Real time computations are on an LSI 11/02 processor; model set up is completed on the host computer, a PDP 11/23. Th



varying look angles off-nadir to form stereopairs (10°, 50°, 80° and −80°).

homologue orientation points is identified and measured, along with ground control points that are visible in either one or in both images. The measurements are used with assumed or otherwise available approximations of the sensor path (position and attitude). In the event that no approximations are available for the sensor path, there is provision for single image space resection based on ground control points. The aim is to establish a flight path prior to entering the stereomodel formation.


0
10km
N

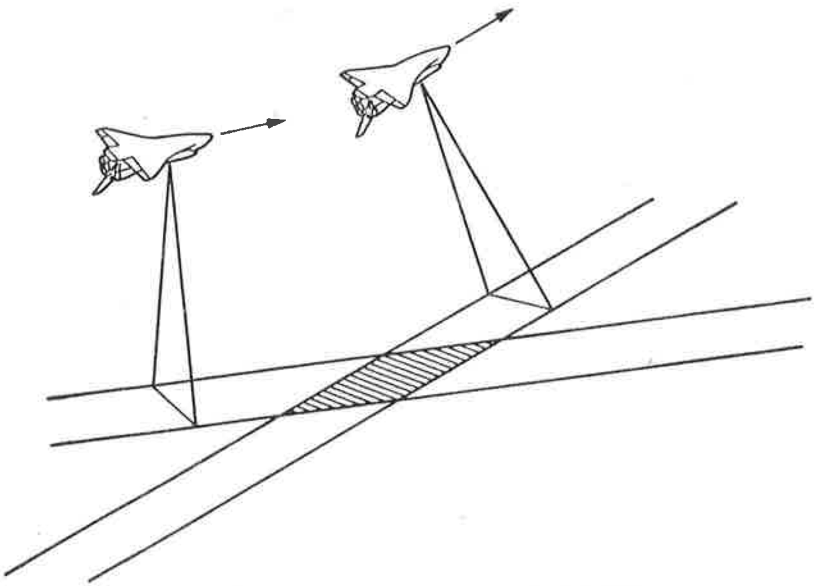


FIG. 5. Radar stereogeometry with intersecting flight lines.

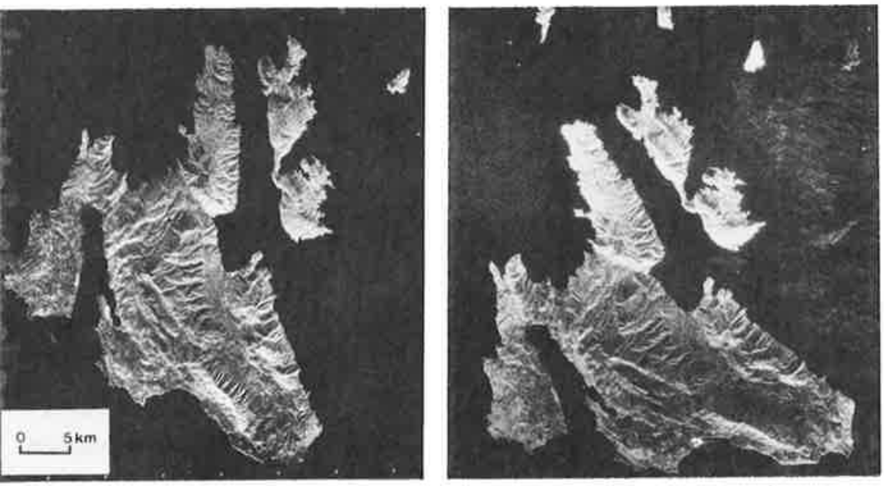


FIG. 6. Overlapping satellite radar image pair; flight lines have an intersection angle of 34°.

Results

A variety of radar stereomodels has been processed through SMART, among them that shown in Fig. 6. Generally it is necessary to measure a larger set of homologue orientation points to ensure the absence of residual y parallax. In the example of a Seasat satellite radar stereomodel, this may be 15 points in an area of 100×100 km.

Mapping accuracies are primarily a function of the sensor and imaging configuration and not of the analysis techniques. Table II illustrates some examples of recent stereomapping accuracies obtained with SMART. The numbers indicate that, so far, a

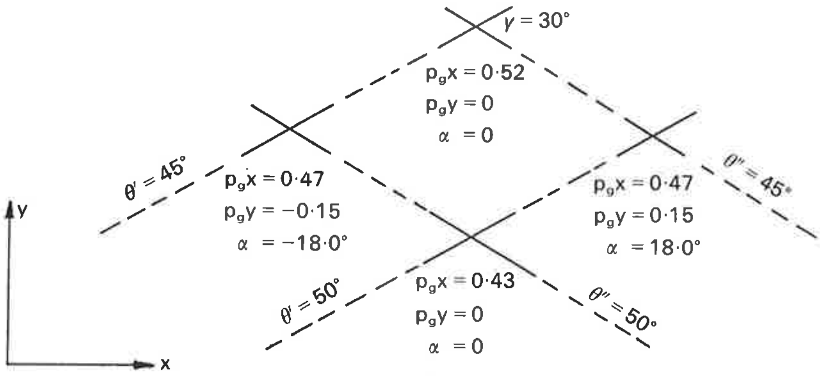


FIG. 7. x and y parallaxes in the stereopair of Fig. 6.

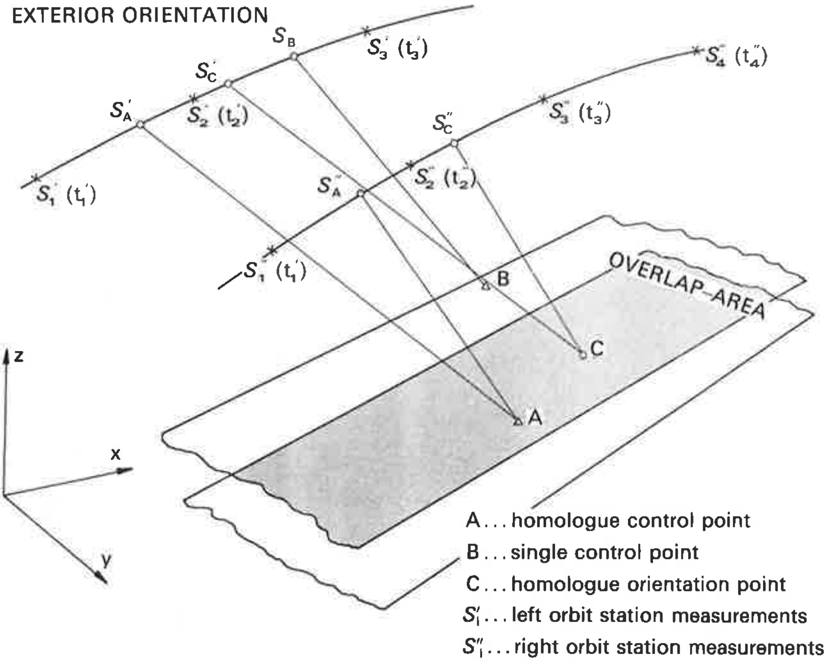


FIG. 8. Definitions for radar stereomodel set up on an analytical plotter.

TABLE II. Radarstereomapping r.m.s. accuracies obtained with an analytical plotter and SMART program. X denotes the along track co-ordinate.

	Radar data and systems					
	Seasat (Los Angeles)			*SIR-A (Greece)*		
Number of ground control points	16	4	2	31	4	3
Number of orientation points	10	0	8	6	0	6

Radiometric Rectification

Concept

The brightness value of a digital radar image pixel is determined essentially by incidence angle (topographic slope), surface texture and dielectric constant, in that order. In many cases, the topographic slope effect must be considered to be a factor that occludes the relevant effects, such as surface texture. A derived image product that does not show image brightness variations due to slope is called here "radiometrically rectified."

Procedure

It is necessary to associate with each image pixel the corresponding ground position and therefore also ground slope. If the image were to display a number of known ground points, one could simply relate it (geometrically rectify it) to the ground co-ordinate system. Usually, however, points are difficult to identify on an image of accentuated relief. Therefore, it appears sensible to simulate a radar image from a given digital elevation model and then to register the real with the synthetic image. This process is feasible even in the complete absence of ground control. Once image and ground are related to one another, it is trivial to eliminate that portion of each pixel's brightness that is due to topographic slope. In fact, this amounts to forming the difference between actual and synthetic image.

Result

Fig. 9 represents a set of data showing (a) the actual raw radar image, (b) the synthetic and (c) the radiometrically corrected one. The latter lends itself to the interpretation of image tone difference as a result of surface properties other than slope. In the example of Fig. 9, this is due to surface cover such as snow, ice, grass and rock.

A number of radar data sets has been processed with this procedure recently. The result has been found very useful for image interpreters since it allowed, for the first time, the separation from one another of effects of phenomena that otherwise were not separable, even if a terrain description existed in the form of a digital elevation model.

Latest Result

The space shuttle had its most recent radar mission during the period of 5th to 13th October, 1984 in the SIR-B experiment. The novelty about this experiment consisted of the alteration of look angles off-nadir that was programmed into the sensor operation. As a result, radar images were obtained at previously unavailable look angle differences.

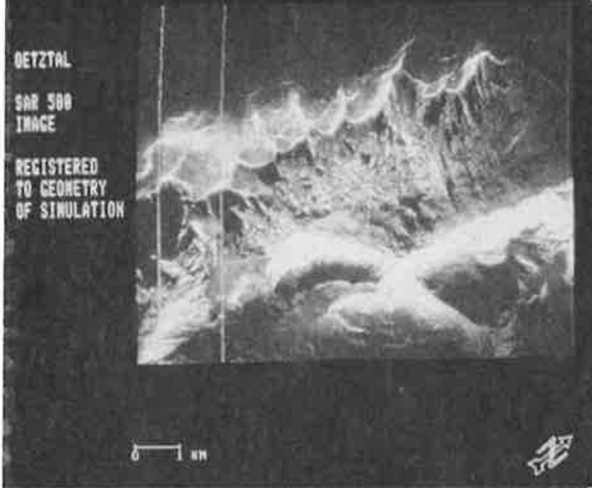
Fig. 10 shows one particular image pair of Mt. Shasta, California. In fact, this particular pair was the first stereo-image pair to be available from that mission. It has look angles of 29° and 57° off-nadir, resulting in nearly 30° stereo-intersection angles. One of the two images suffers from poor signal to noise ratio due to a problem during data acquisition aboard the shuttle.

The stereopair of Fig. 10 was subjected to processing with SMART on the DSR-1 analytical plotter*. This resulted in contour lines and a digital elevation model as illustrated in Figs. 11 and 12, with an accuracy of about ± 90 m, employing about 10 natural ground control points. It should be noted that this accuracy is also about twice the ground resolution; however, one of the two images suffers from a distinct lack of quality. Since SIR-B produced a larger number of stereomodels, some additional processing is required to establish a more representative value for the accuracy potential of SIR-B stereomapping.

An Application in Sea Ice Motion Studies

An obvious application of satellite radar images is to the study of arctic sea ice. The phenomena vary rapidly, the weather typically does not favour passive sensing in the visible portion of the electromagnetic spectrum, and the winters are long and dark.

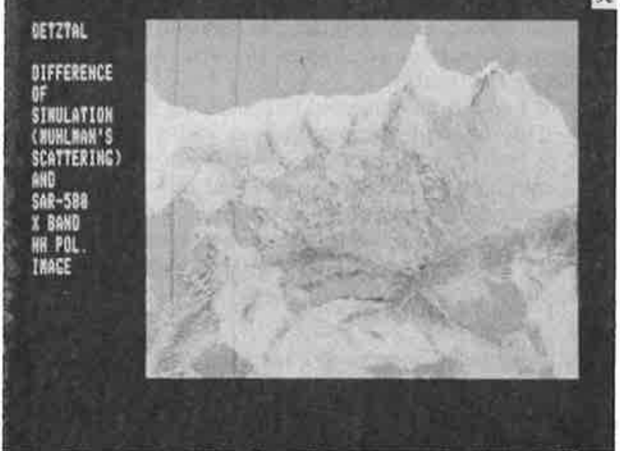
9a


OETZTAL
SAR 580
IMAGE
REGISTERED
TO GEOMETRY
OF SIMULATION
0 1 KM

9b


OETZTAL
0 1 KM
SIMULATED RADAR IMAGE

9c


OETZTAL
DIFFERENCE
OF
SIMULATION
(MUHLMAN'S
SCATTERING)
AND
SAR-580
X BAND
HH POL.
IMAGE

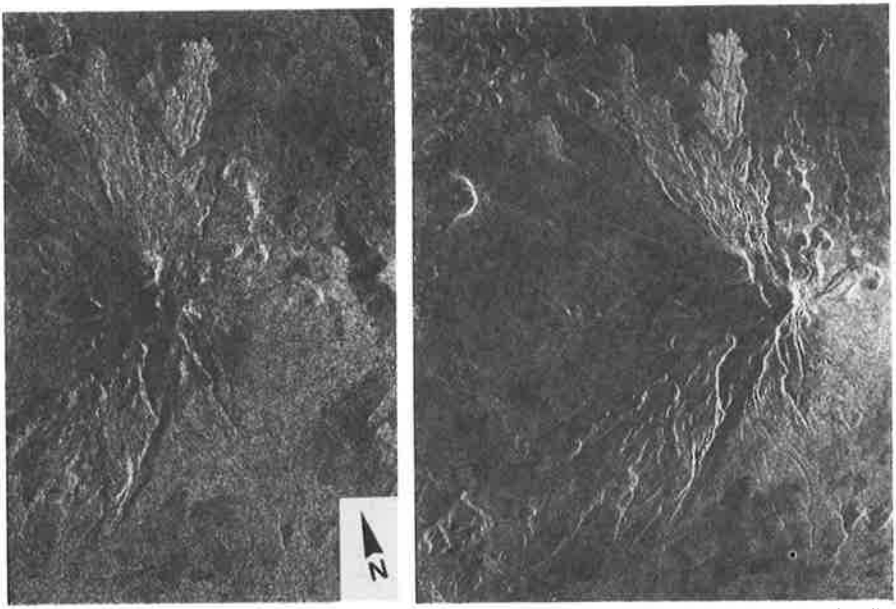


FIG. 10. Space shuttle SIR-B radar image pair of Mt. Shasta, California, at 24° and 57° look angle off-nadir.

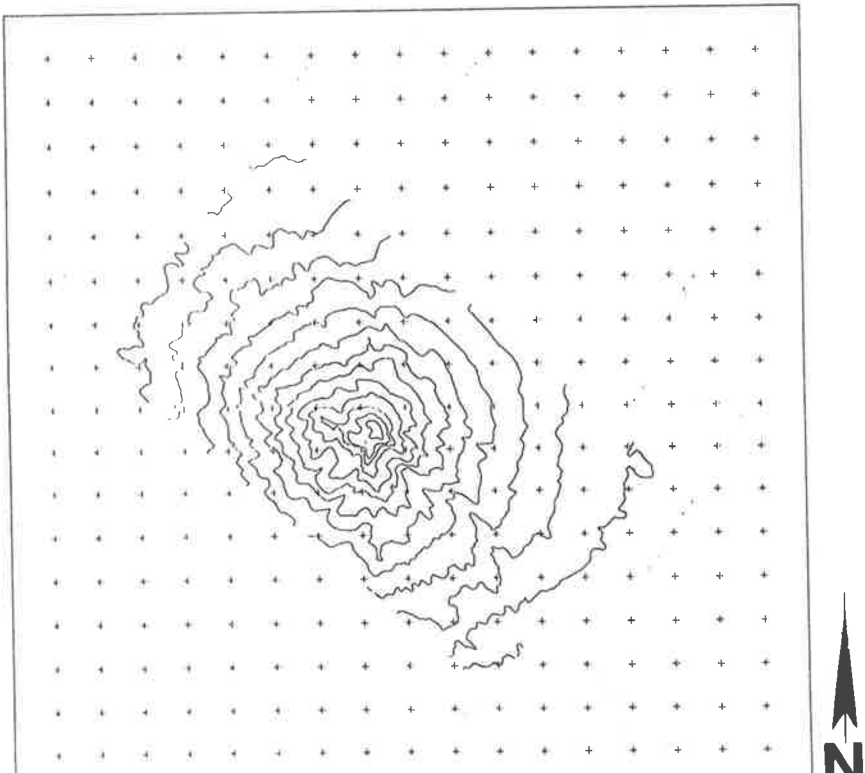


FIG. 12. Mt. Shasta topographic relief as obtained from radar stereo-images in Fig. 10.

Seasat provided unique sequential sea ice coverages by long radar image strips. Fig. 13 illustrates a typical set. These data have been studied and a set of sea ice features could be successfully tracked over a period of one month. The details of the study were presented by Leberl *et al.* (1983). The accuracy of ice feature positions amounted to about ± 150 m. The ice motion was found to be about 180 km during the month. The motion itself is shown in Fig. 14.

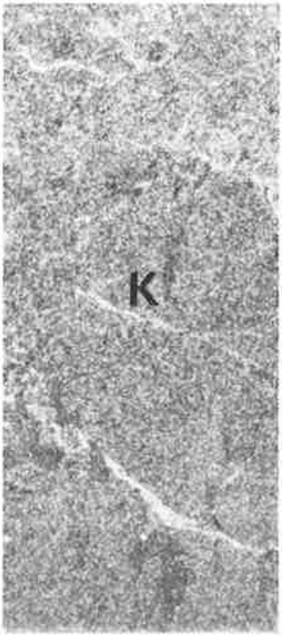
OUTLOOK

A recent radargrammetric review paper described in detail the status of the subject (Leberl, 1983). The current contribution serves to address some more recent radargrammetric developments that were not discussed in the earlier review. This is significant since some new work has been performed based on image simulation and on photogrammetric radar stereomapping. This work was motivated by thematic analysis needs and by the planned project to map the planet Venus in the Venus Radar Mapper (VRM) mission. This is the successor to the earlier Venus Orbital Imaging Radar (VOIR) concept.

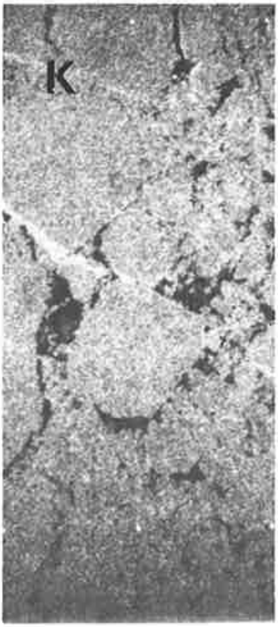
The paper outlines radar image simulation and its application to parameter studies regarding stereoscopic viewing, flight direction, look angles, and squinted mode imaging; it addresses radar stereomapping on an unmodified analytical plotter and it discusses radiometric rectification of image pixel gray values.

The application of radargrammetry to actually perform some relevant task is feasible in topographic and planimetric mapping at small scales and in specific thematic contexts, such as in geology, or land and sea ice monitoring.

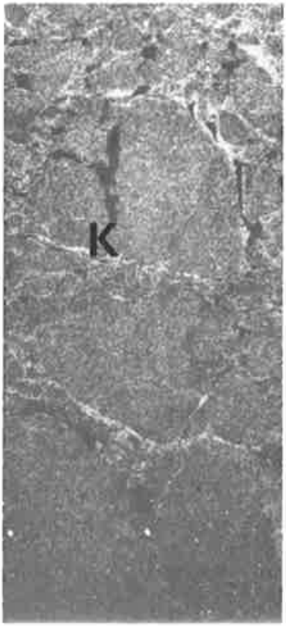
The near future will see a refinement of analysis techniques, wider distribution of analysis methods, availability of data sets *via* satellite missions in the space shuttle



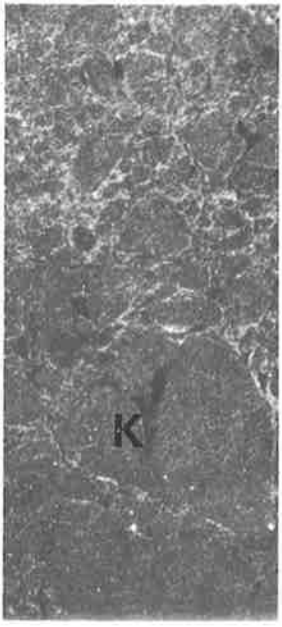
1038



1081

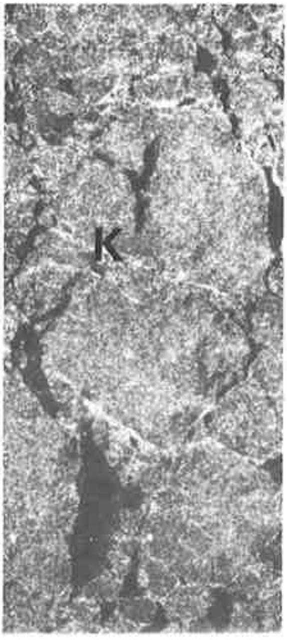


1296



1339

1382



1425

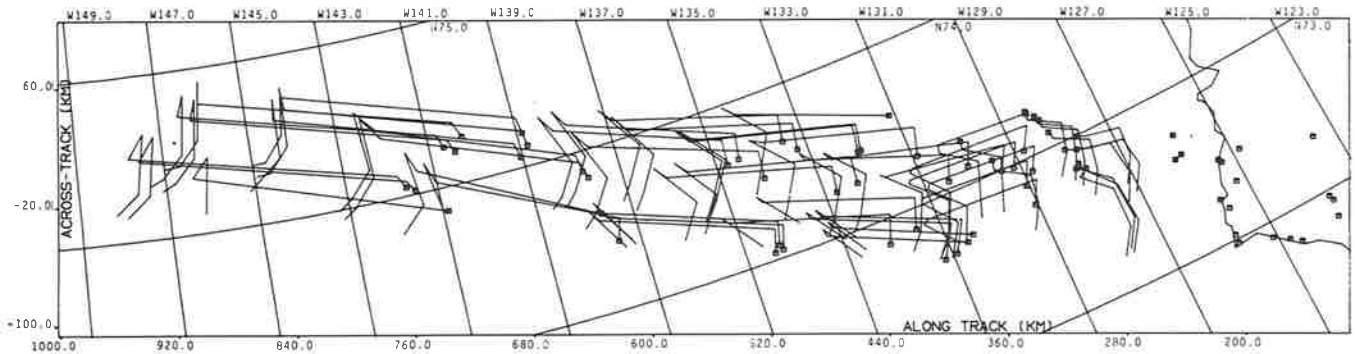


FIG. 14. One month sea ice motion tracked with the help of Seasat radar images (from Leberl *et al.*, 1983).

data has not yet been tapped. It is evident from this review that there is very little to report in these areas. However, the outlook for radargrammetric work must include a strong reference to these concepts, should radar images become a viable element in the total remote sensing tool kit.

ACKNOWLEDGEMENTS

This paper has benefited from work done by several individuals at the Graz Research Center, in particular J. Raggam and H. Fuchs. Typing was done by P. Funston of the Markhurd Corporation. This support is gratefully acknowledged. The research also was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

REFERENCES

AUTOMETRIC, 1982. *Program documentation for analytical mapping system radar model.* Prepared by Autometric, Inc., Falls Church for USA Engineer Topographic Laboratory, Ft. Belvoir, Virginia. 36 pages.

BAIR, G. L. and CARLSON, G. E., 1974. Performance comparison of techniques for obtaining stereo radar images. *IEEE Transactions on Geoscience Electronics*, GE-12(4): 114–122.

DOMIK, G., KOBRICK, M. and LEBERL, F., 1984b. Analyse von Radarbildern mittels Digitaler Höhenmodelle. *Bildmessung und Luftbildwesen*, 52(5): 249–263.

DOMIK, G., LEBERL, F., KIENEGGER, E. and RAGGAM, J., 1985. *Study on the use and characteristics of SAR for geological application. Radargrammetric aspects.* ESA Study Contract 5443/83/D/IM (Sc) (ESOC Darmstadt). Graz Research Center, Austria. 50 pages.

DOMIK, G., LEBERL, F. and KOBRICK, M., 1984c. Radar image simulation and its application in image analysis. *International Archives of Photogrammetry and Remote Sensing*, 25(3a): 99–108.

DOMIK, G., LEBERL, F. and RAGGAM, J., 1983. *Evaluation of radargrammetric stereo.* DIBAG Report 11. Graz Research Center, Austria. 127 pages.

DOMIK, G., RAGGAM, J. and LEBERL, F., 1984a. Rectification of radar images using stereo-derived height models and simulation. *International Archives of Photogrammetry and Remote Sensing*, 25(3a): 109–116.

DOWMAN, I. J. and MORRIS, A. H., 1982. The use of synthetic aperture radar for mapping. *Photogrammetric Record*, 10(60): 687–696.

GUERTIN, F. and SHAW, E., 1981. *Definition and potential of geocoded satellite imagery products.* Presented paper, Canadian Symposium on Remote Sensing, Winnipeg, Manitoba. Obtainable from Canadian Centre for Remote Sensing, 717 Belfast Rd., Ottawa, Ontario K1A 0I7.

HOLTZMAN, J. C., FROST, V. S., ABBOT, J. L. and KAUPP, V. H., 1978. Radar image simulation. *IEEE Transactions on Geoscience Electronics*, GE-16(4): 296–303.

KAUPP, V. H., BRIDGES, L. C., PISARUCK, M. A., MACDONALD, H. C. and WAITE, W. P., 1982. *Comparison of simulated stereo radar imagery.* Presented at IGARSS, Munich. Paper TA4.

KOBRICK, M., LEBERL, F. and RAGGAM, J. (submitted). *Convergent stereo with shuttle imaging radar.* Manuscript, Jet Propulsion Laboratory. Pasadena, California.

KONECNY, G., SCHUHR, W. and WU, J., 1982. Untersuchungen über die Interpretierbarkeit von Bildern unterschiedlicher Sensoren und Plattformen für die kleinmassstäbige Kartierung. *Bildmessung und Luftbildwesen*, 50(6): 187–200.

LAPRADE, G. L., 1963. An analytical and experimental study of stereo for radar. *Photogrammetric Engineering*, 29(2): 294–300.

LEBERL, F., 1983. Photogrammetric aspects of remote sensing with imaging radar. *Remote Sensing Reviews*, 1(1): 71–158.

LEBERL, F., FUCHS, H. and FORD, J. P., 1981. A radar image time series. *International Journal of Remote Sensing*, 2(2): 155–183.

LEBERL, F., RAGGAM, J., ELACHI, C. and CAMPBELL, W. J., 1983. Sea ice motion measurements from Seasat SAR images. *Journal of Geophysical Research*, 88(C3): 1915–1928.

LEVINE, D., 1960. *Radargrammetry.* McGraw-Hill Book Co., New York. 330 pages.

MACDONALD, H. C. and WAITE, W. P., 1971. Optimum radar depression angles for geological analysis. *Modern Geology*, 2: 179–193.

NORVELLE, F. R., 1972. AS-11A radar program. *Photogrammetric Engineering*, 38(1): 77–82.

RAGGAM, J. and LEBERL, F., 1984. SMART—a program for radar stereo mapping on the Kern DSR-1. *Proceedings, Annual Meeting of the American Society of Photogrammetry*, 765–773.

RINNER, K., 1966. Die Geometrie des Funkmessbildes. In Jordan/Eggert/Kneissl, *Handbuch der Vermessungskunde*, VI. Metzlersche Verlagsbuchhandlung, Stuttgart. Originally published in 1948 by the Austrian Academy of Sciences, Vienna.

WILDEY, R. L., 1983. *Topography from single radar images.* Northern Arizona University, Flagstaff, Arizona. 9 pages. Unpublished.

Résumé

L'histoire de la radargrammétrie remonte à environ 35 ans. Elle a commencé avec les premiers enregistrements de radar issus des indicateurs de position à écran panoramique (PPI) de 1948, pour aboutir au radar imageur actuel, SIR-B, de la navette spatiale (1984). Si l'on considère l'avenir, on peut se féliciter par avance des projets comme ceux des satellites de télédétection prévus pour 1989, tant japonais qu'européens (ERS-1) ou comme la mission de cartographie radar sur Vénus (VRM) prévue par la NASA en 1988.

Pour développer les applications cartographiques du radar, il faut disposer de méthodes capables de traiter aussi bien des images séparées, que des couples stéréoscopiques ou des blocs comprenant plusieurs bandes d'images. La forme essentiellement numérique que revêtent ces données, incite à mettre en oeuvre en radargrammétrie des méthodes utilisant les systèmes de traitement d'images numériques, pour effectuer des redressements, extraire des modèles numériques du terrain et rendre superposables des images multidates de façon à mettre en évidence les évolutions.

Cet article présente une analyse des connaissances radargrammétriques actuelles, des applications et des développements attendus.

Zusammenfassung

Die Geschichte der Radargrammetrie umfasst etwa einen Zeitraum von 35 Jahren. Sie hat sich von anfänglichen Lagesicht-Radaraufzeichnungen im Jahre 1948 zu dem gegenwärtigen, im Space Shuttle verwendeten Abbildungsradar (1984, SIR-B) entwickelt. Für 1989 sind die europäischen und japanischen Fernerkundungssatelliten ERS-1 und für 1988 die Venus-Radar-Kartierer-Mission (VRM) der NASA geplant. Die Kartenanwendung erfordert, dass Methoden für Einzelbilder, Stereobildpaare und Blöcke von Bildreihen zur Verfügung stehen. Das vorherrschend digitale Datenformat spricht dafür, dass radargrammetrische Verfahren in Systeme der digitalen Bildverarbeitung zur Entzerrung, Gewinnung digitaler Geländehöhen und zur Multibildregistrierung zum Zwecke der Erkennung von Veränderungen implementiert werden sollten. Der Beitrag gibt eine Übersicht zum gegenwärtigen Verständnis der Radargrammetrie, ihrer Anwendungen und zu erwartender Entwicklungen.

DISCUSSION

Chairman (Mr. D. A. Wallis): Thank you very much indeed, Dr. Leberl, for a most interesting paper. May I start the discussion myself? As the resolution increases, doesn't radar then become less of an all weather sensor because it's well known that, in approaching high frequencies, there is scatter from moisture particles in the air which degrade the all weather capability?

Dr. Leberl: Theoretically in a synthetic aperture radar, the geometric resolution is unrelated to the wavelength. The theoretical limit of resolution is half the diameter of the real antenna. So one can think of a satellite radar that transmits enough energy to take advantage of an extremely long synthetic antenna and which would illuminate a very wide area using a very small antenna. One could then achieve a geometric resolution better than 1 m from space.

I mentioned in my oral presentation that higher resolution doesn't really solve the problem with radar. The reason is that as the resolution increases, the system becomes more sensitive to small surfaces that are flat and so, in encountering non-natural surfaces, such as roads, houses and walls, there is greater specular return. Since I do not have the appropriate secrecy clearance, I have not seen very high resolution radar images. Incidentally, if I had, I wouldn't be allowed to talk about them! I only know images with a resolution of about 2 m from the SAR-580 campaign of the European synthetic aperture radars and the degree of specular return; in many cases, one tends to average digital pixels to eliminate the specular reflection. As one averages pixels with some type of low-pass filter, there is a reduction in the geometric resolution. It is therefore my understanding that at present we cannot really expect great enhancement in geometric resolution much beyond 2 m or 3 m.

Chairman: Did you have to write new software routines for the DSR-1 in order to be able to form the radargrammetric models?

Dr. Leberl: We wrote the plate processor programs for radar as well as the resection in space, the approximate solutions and so forth. We're not using Kern software to map from radar.

Dr. Muller: Will you always require DEM data in order to remove layover effects?

Dr. Leberl: That is a short and difficult question and is actually two questions packed into one. First: will one always require digital elevation models to do a geometric or radiometric rectification? Second: is it possible to produce a rectified image where the layover is corrected? "Layover" is the effect where a tower image is falling toward the nadir and therefore is laid over the image of the ground. Let me reply to the second question. We cannot unravel from the single grey tone in one pixel the two individual reflections from the ground and from the tower, There is no way of successfully eliminating layover as I have defined it earlier. However, there is a way of rectifying other geometric defects, namely, displacements of features that are not in the datum plane. Layover is not only a geometric problem, but a problem of added intensity values that come from two sources. Let me reply to the first question. I have shown that one can generate a digital elevation model from a set of radar images. Therefore, we can use that digital elevation model to correct the geometry and radiometry of the image; I claimed in the past that that makes sense. However, it makes sense only if the digital elevation model is detailed and accurate enough. If it isn't, we need an externally provided digital elevation model. We used SIR-A radar images of Cephalonia and produced a digital elevation model; this was entered into the rectification process. However, the quality of the data was not very high; therefore, the rectification wasn't very good.

Dr. Dowman: You've given us a lot of exotic applications of a number of techniques, but do you think that radar has any application to the rather mundane problems of topographic mapping or map revision in areas which have a high percentage of cloud cover?

Dr. Leberl: I am well aware of your 1982 paper on the interpretability of radar images for planimetric mapping at small scales and the conclusion that radar images cannot satisfy the common needs for planimetric mapping. I was not surprised and have never proposed the application of radar to regular topographic mapping. I don't believe it can be used for mundane topographic mapping.

The problem has concerned me for some time. I notice repeatedly in developing countries that there is photographic coverage, produced, for example, through foreign aid, that is not converted into maps. Areas covered by these photographs will be mapped by radar. There were no maps available and the capability to make maps is absent. The use of radar surveys may not seem justified in the presence of photographic coverage, were it not for the simplicity of logistics and the rapid availability of the result. Justifying a radar survey is not a straightforward matter, but reconnaissance type radar maps are produced because a result is needed very quickly.

Chairman: Dr. Leberl made a great effort to be with us tonight. He's an extremely busy person and we very much appreciate his participation at our meeting.