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Side-Looking Radar Mosaicking Experiment

A numerical sequential radar block adjustment resulted in improved accuracy in the mosaicking of radar images.

(Abstracts on next page.)

INTRODUCTION

CURRENTLY PRODUCED side-looking radar image mosaics were accurate to within an RMS point error of about ±150 m. This was concluded from a unique set of 24 overlapping side-looking radar strips flown over a well-mapped area of more than 90,000 km² covering parts of Ohio, West Virginia, Virginia, and Kentucky. The topographic maps at a scale 1:24 000 that covered the imaged area permitted an analysis of the errors of individual radar images and of the final radar mosaics.

We have taken advantage of this extensive radar coverage of well-mapped terrain to analyze the accuracy of some of the radar mosaicking methods that are currently applied. We have attempted to obtain some quantitative insight into the effect of the density and distribution of ground control points on the accuracy of the final radar mosaic.

The data confirm the expectation that a numerical sequential radar block adjustment provides results that are significantly more accurate than those obtainable from a direct mosaicking process based on tielines (resulting in so-called semi-controlled mosaics). We also conclude that the use of tielines cannot very well be justified by either the mapping accuracy, or by the convenience of the mosaicking process.

These conclusions are developed in a series of numerical experiments based on measurements of pricked points in the common areas of overlapping radar strips. We will describe the image data and measurements and follow this with an outline of presently applied radar mosaicking procedures. The discussion of the achieved results will then provide the evidence on which the above conclusions are based.

IMAGE DATA AND MEASUREMENTS

An area of about 400 × 250 km² in Ohio, West Virginia, Virginia, and Kentucky (Figure 1) was imaged using the Goodyear Aerospace Corp. GEMS 1000 synthetic aperture radar system which is operated aboard an inertially guided Caravelle twin jet of Aero Service Corporation. Ground resolution of the images is about 12 × 12m². As in most missions with this system, the aircraft flies at an altitude of about 12 km and follows the meridian within the accuracy of the inertial guidance system. The imagery employed in the mosaicking experiment was thus acquired in north-south oriented flight lines, with the radar looking west. A side-lap of 20

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ABSTRACT: *A block of 24 overlapping synthetic aperture side-looking radar images flown over a well-mapped area of about 90,000 km² covering parts of Ohio, West Virginia, Virginia, and Kentucky provided an opportunity to evaluate the mapping accuracy achieved in current radar mosaicking projects. The maps of scale 1:24 000 that are available in the imaged area permitted the study of the geometric errors of the radar mosaics and of individual radar strips. An estimate was obtained for the effect of the distribution and density of ground control points and for the accuracy of different mosaicking methods that are currently employed with synthetic aperture radar images. It is shown that a successful radar mosaicking process requires the elimination of image errors of up to several kilometers. These errors are introduced as a result of the limited precision of the inertial aircraft navigation. An example of a radar mapping effort in which the navigation errors could be eliminated is presented. The resulting radar mosaics have residual* RMS *mapping errors of planimetry of about ± 150 m.*

ZUSAMMENFASSUNG: *(Ein Experiment ueber die Herstellung von Radar-Bildplaenen Ein Gebiet von etwa 90 000 km² in Teilen Ohios, West Virginias, Virginias und Kentuckys wurde durch ein Radarsystem mit synthetischer Antenne abgebildet, sodass ein Block von 24 ueberlappenden Seitwaerts-Radar Bildern erhalten wurde. Diese Daten ermoeglichen ein Experiment zur Emittlung der Kartiergenauigkeit, die in gegenwaertigen Radarprojekten erreicht wird. Die Karten im Masstab . . .1:24 000, welche im aufgenommenen Gebiet vorhanden sind, erlauben eine Untersuchung . . . der geometrischen Verformungen einzelner Bildstreifen und der Bildmosaike. Weiters kann der Zusammenhang zwischen der Kartiergenauigkeit, der Dichte und Verteilung von geodaetischen Kontrollpunkten sowie einiger Methoden der Bildplanerstellung untersucht werden. Die Arbeit zeigt, dass die urspruenglichen Radarbildstreifen Verformungen bis zu einigen Kilometern haben koennen, die durch die beschraenkte Genauigkeit der Flugzeugtraegheitsnavigation verursacht werden. Es wird jedoch gezeigt, dass diese Fehler in der Herstellung von Radarbildplaenen durch eine numerische Blockausgleichung eliminiert werden koennen, sodass die verbleibenden mittleren Fehler de Radarbildplaene etwa ± 150 m betragen.*

RESUME: *Un radar à ouverture synthétique a été utilisé pour imager une surface bien cartographiée d'environ 90 000 km² couvrant en partie les états d'Ohio, Virginie de l'Ouest, Virginie et Kentucky. Un groupe de 24 images a permis d'évaluer la précision cartographique atteinte dans les mosaiques d'images radar. Des cartes à l'échelle de 1:24 000 qui sont disponibles pour la région, ont permis l'étude des erreurs géométriques des mosaiques et des images simples. Une estimation des effets de la distribution et de la densité des points d'appui a été obtenue, ainsi qu'une estimation de la précision des différentes méthodes de construction des mosaiques, qui sont employées pour le radar à ouverture synthétique. Il est demontré qu'une procédure exacte pour une mosaique d'images radar nécessite l'élimination d'erreurs jusqu' à plusieurs kilomètres. Ces erreurs résultent de la précision limitée du système de navigation a inertie de l'avion. Cette contribution présente un exemple de cartographie au moyen d'un radar. Dans cet exemple les erreurs de navigation ont pu être éliminées. Les mosaiques finales ont une erreur planimétrique d'environ 150 m.*

per cent, and a pair of east-west tielines along the northern and southern perimeter, were available to tie the individual images into a coherent block.

Measurements were taken of the points in the overlap common to adjacent images to merge the individual strips, and of ground control points to transform the radar data into a map coordinate system. The common points were carefully selected and marked on the emulsion of the diapositives at a scale 1:400,000 using a Wild PUG point transfer device (estimated accuracy about ± 2 μm). The image coordinates of the marked points then were measured on a Haag-Streit Coordinatograph (estimated accuracy about ± 50 μm) and the map coordinates of the ground control points were scaled off the 1:24,000 maps of the area.

More than 200 different points were measured, including some 65 ground control points and a large number of tiepoints that were selected at approximately 12-cm intervals along the image strips (about 50 km on the ground) and, due to the 20 per cent overlap, were measured twice.

Radar Mosaicking Procedures

Four techniques of side-looking radar mosaicking have so far been, or are presently being, employed. The simplest method is one in which hardly any ground control points are available or used and where no preprocessing is applied. The individual radar strips are directly laid out on a mosaicking board in such a way that adjacent images fit together; but an adjustment to ground control, if available, is not carried out beyond a preliminary overall rotation, scaling, and shifting to the map coordinate system. Basically, the resulting radar mosaic is as accurate as the inner geometry of the images and the aircraft navigation permit (1 km error per hour of flight).

Fig. 1. Location of radar mapping area.

The most sophisticated and expensive radar mosaicking method thus far employed was based on continuous simultaneous SHORAN tracking of the survey aircraft from two geodetically surveyed ground stations. As a result, the position of the aircraft was determined to an absolute accuracy of about ± 300m (van Roessel *et al.*, 1974). This in turn permitted the transformation of an ordered set of artificial radar image points (so called "range marks") into the map system. The transformed set of image points represents the base-map onto which the mosaic is laid out. The method was, for example, employed in the first phase of Brazil's RADAM. Although it provides information for the rectification of individual radar strips prior to mosaicking, it was soon abandoned, apparently due to cost considerations. The accuracy of the resulting mosaic is determined by the precision of the SHORAN aircraft tracking system, the effect of measuring errors, and weaknesses of the image geometry. It must therefore be expected that SHORAN controlled radar mosaicking leads to RMS errors certainly well in excess of ± 300 m (van Roessel *et al.*, 1974).

Because SHORAN tracking determines the mosaicking accuracy, this has been thus far the only method for which a reliable estimate was available for the accuracy of the mapping product. For this reason, but more so because there was no SHORAN tracking provided in the acquisition of the test data, the SHORAN based method of radar mosaicking will not be numerically evaluated in this paper.

A rather frequently used mosaicking method relies on at least two or more "tielines"; these are radar image strips flown across the direction of the production imagery along the perimeter of the mapping area. A number of ground points are then surveyed or scaled off an existing map and marked on the tielines or the tielines are tracked by SHORAN. This permits their transformation into the map system. The production images are then laid out on the mosaic board to achieve a fit to the tielines and a smooth transition at adjacent image strips. The root-mean-square errors of this method have been estimated (for SHORAN tracking of tielines) by van Roessel *et al.* (1974) to be about ± 700 m. However, it is the most widely used procedure, for example being employed in the entire radar mapping effort of Brazil (9 mil. km^2), except for the initial part with complete SHORAN control of all flights. An obvious advantage of the method based on tielines is its simplicity: No numerical operations are required and the mosaic can be compiled directly. But among the disadvantages of the method are a limited accuracy, a lack of the possibility to adjust the mosaics to ground control points other than the ones imaged by the tielines, and the fact that there is no information available for the rectification of individual image strips prior to mosaicking.

The fourth method of radar mosaicking is based on a numerical radargrammetric block adjustment. Here, measurements of points in the overlap areas of adjacent images are used to tie the images into a block, and the block is transformed into a network of ground control points similar to a photogrammetric block adjustment. This method of preparing a base map for mosaicking was employed in PRORADAM, Colombia's radar mapping project of the Amazon, described in detail by Leberl (1975a). A numerical sequential adjustment of radar images using spline polynomials (first, block formation as an internal adjustment, then fit to the ground control points in an external adjustment) produces results that appeared quite comparable to or, in the case of certain constraints, even better than a simultaneous adjustment of radar images (Leberl, 1975b). It is thus the sequential method of numerical radar block adjustment that is considered in the present practical experiment in which we aim at establishing accuracy models for radar mosaicking. One can expect a numerical block adjustment to result in mosaics of high accuracy, and to produce information for the rectification of the images prior to mosaicking. For details on numerical side-looking radar block adjustment algorithms, reference is made to earlier publications (Leberl, 1975a and 1975b).

Radar Mosaicking Results

The mosaicking experiment is based on the numerical treatment of the radar image measurements and map coordinates. The first step was to tie all radar images into a block in an internal adjustment. The block was then transformed into the network of known ground control points by using a linear conformal transformation. Figure 2 presents the result with error vectors indicating that there was a significant overall affine deformation of the radar block which amounts to about 3 per cent (scale is larger in the north-south than the east-west direction). The root-mean-square (RMS) discrepancies amount to about ±3.5 km.

A portion of this deformation is artificially built into the optical correlation process to compensate for later differential paper shrinkage. The random errors of the optical correlation process generally do not contribute a significant portion to the overall errors of the final image (Peterson, 1976). Figure 3, cases *(a)* to *(k)*, present the RMS errors encountered in the check points if an interpolative correction is applied to the radar block coordinates (external adjustment). Checkpoints are those groundpoints which do not take part in the adjustment, but only serve the purpose of evaluating the accuracy. The figure illustrates the distribution of the ground points employed for computing corrections. The method of computation was with weighted moving averages (see, for example, Schut, 1970; or Leberl, 1975c).

Case *(l)* of Figure 3 specifically addresses the mosaicking results employing tielines. The results are not obtained from actually compiling a mosaic using tielines. Instead, this process was numerically simulated. First, the tielines were adjusted to the available ground control. Then the north-south lines were adjusted sequentially to the

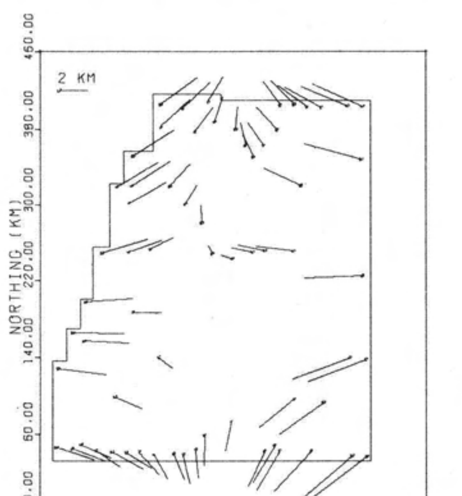

Fig. 2. Distribution of ground control points and vector representation of the discrepancies encountered between the internally adjusted block and the ground control point, prior to external adjustment.

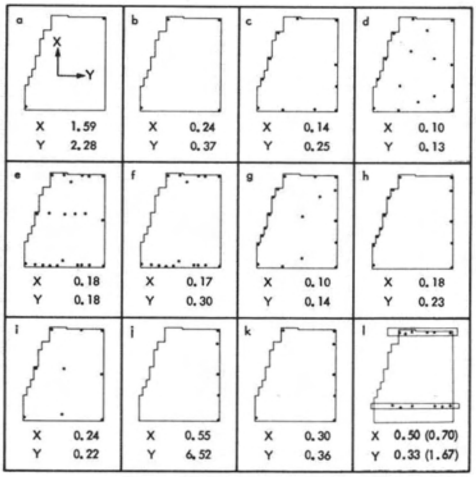

FIG. 3. Radar mosaicking results using various arrangements of ground control points (cases *(a)* to *(k)*) and an approach based on tielines (case *(l)*). The results are RMS discrepancies between radargrammetric and map coordinates of checkpoints, given in kilometers.

tielines and to the one previously adjusted adjacent north-south line by using a spline fit. The accuracy estimate for the tielines method might thus be too optimistic if one assumes that the numerical approach using splines is too flexible and accurate to be a valid simulation of the "damp and stick" process of mosaicking images on wet photo paper. The two sets of results for case *(l)* of Figure 3 concern two different assumptions for the numerical approach to mosaicking with tielines. This will be discussed in the next section.

Upon completion of the radar block adjustment, information is available on the discrepancies among adjacent individual radar strips and on their internal geometric errors. Figure 4 illustrates the dominant appearance of the errors of individual strips. They are slowly varying and fully explainable by the so called "Schuler-periodic" errors of the inertial navigation. These errors theoretically have a period of 84 minutes of flight and an amplitude that grows at a rate of about 1 km-per-hour or more. The numerical approach revealed that in the present example the Schuler-periodic velocity errors had amplitudes far in excess of what one must normally expect from a properly operating platform. The numerical approach permits elimination of these errors. The residuals encountered in the images after filtering of the Schuler periodic and overall errors had an RMS value of about ±50 m on the ground and included the effects of measuring errors and parallax differences due to topographic relief.

Topographic relief was not considered in this experiment. Instead, the mapping area was assumed to be flat. This has been so far a rather commonly applied assumption for radar mosaicking. Attempts to differentially rectify radar images and thus to consider topographic relief in mapping have been reported only by a U. S. military mapping research group, but have not been further pursued (Yoritomo, 1972). Effects of topographic relief, however, represent the limit of the mosaicking accuracy. Figure 5 illustrates that topographic relief creates parallax differences in the cross-track (east-west) direction that are much smaller than the overall discrepancy between a point in the radar mosaic and in the topographic map. For the example of the relief of 200 m (occurring in the present mapping experiment), the parallax difference would amount to about 50 m, but the overall relief displacement is 150 m. These are also the accuracy figures obtained for the irregular component of the dis-

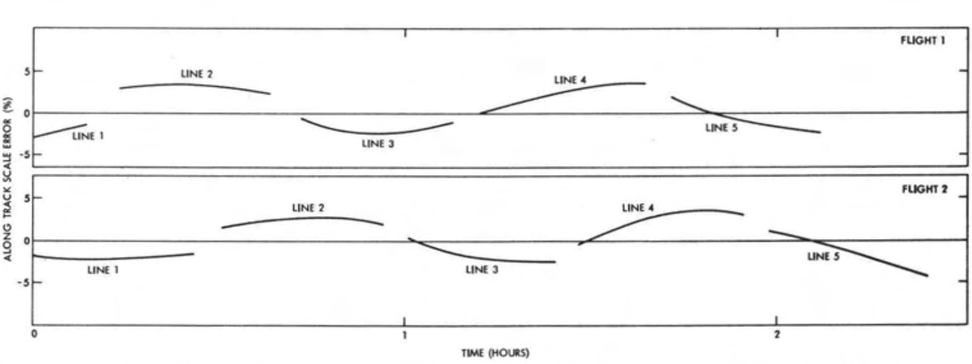

FIG. 4. Curves representing the along-track scale error of image strips acquired during two flights, each producing five flight lines.

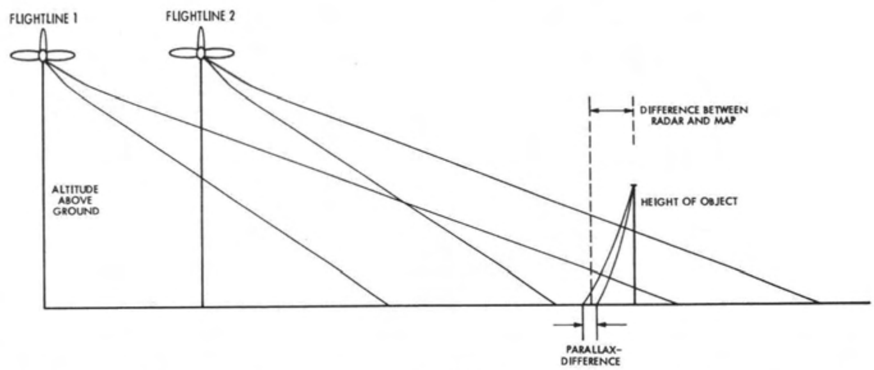

FIG. 5. Relief displacement and parallax difference in the overlap of adjacent radar images.

crepancies among adjacent radar strips (±50 m) and of the mosaic error (±130 m). However, as long as radar mapping is based on mosaicking without differential rectification, there is no point in accounting for errors due to topographic relief. But if the radar block adjustment is carried out in three dimensions instead of in planimetry only, then a preliminary study by DBA systems (1974) seems to indicate that the resulting planimetric accuracy could be significantly improved.

Discussion of Mosaicking Methods and of Point Distribution

It is quite obvious from Figure 3, that the simple mosaicking method, which only would use ground control for orientation and scaling of the mosaic, produces the least accurate results. In the case presented, the mosaicking errors amount to about ±3 km (Figure 3, case *(a)*. This probably is the lower limit for most radar mapping projects based on inertial guidance due to the fact that it results from five-hour mapping flights with excessively large Schuler type errors.

The accuracy of the tieline method of mosaicking is also clearly inferior to the results obtainable from a block adjustment (compare Figure 3, cases *(d)* and *(l)*). There are several reasons for this: Tielines provide only two bands of control, whereas a numerical adjustment can take advantage of any type of control distribution; the tielines only control the overall along-track scale of the production imagery, but not the critical effect of the radar image curvature and differential along-track scale variation; and in the tieline approach unrectified images have to be mosaicked. Actual tieline mosaicking could be less accurate than suggested in Figure 3 for the reason mentioned before. Figure 3 is the result of a numerical simulation rather than actual tieline mosaicking. Numerical treatment of accurate measurements could be more accurate than manual mosaicking.

Case *(l)* of Figure 3 presents two results. The root-mean-square errors in brackets give the accuracy of the tieline approach if no rectification of the individual radarstrips is assumed. The errors therefore reflect the effect of the large overall scale difference of 3 per cent between the across- and along-track direction. The errors given without brackets present the result if the overall affinity of 3 per cent can be detected and rectified.

The tieline case is the only one in which the *X*-coordinates were found to have larger errors than the *Y*-coordinates. No obvious explanation can be offered for this reversal of the accuracy behavior. The error in transferring points from the north-south lines to the tielines is rather large, perhaps of the order of magnitude of ±200 m, because no stereo transfer is possible; relief displacement is towards the north *(X*-direction). However, it is not felt that these considerations sufficiently explain the fact that errors are larger in the *X*-direction than they are in *Y*.

An analysis of various control point configurations reveals that, in a numerical approach, four control points can eliminate the large overall affine deformation of the radar block (Figure 3, case *(b)*). Furthermore, in a sequential adjustment procedure, a fairly regular distribution of control points produces the highest accuracy (Figure 3, case *(d)*), and a densification of the control network improves the results (cases *(b)*, *(i)*, *(g)*, *(d)*). If only perimeter control is available, then the mapping accuracy reduces somewhat, although not dramatically (Figure 3, cases *(c)*, *(f)*, *(h)*). It appears that control along the perimeters in the flight direction is more essential than across the flight direction. Along-track scale is well transferred across adjacent strips, but the effect of the strip's curvature can be eliminated only by at least one linear array of control points in the flight direction.

Cost

In a comparison of the effort that would have to be expended for the various mosaicking techniques, it seems obvious that a lack of consideration of ground control points would result in a less expensive mosaicking effort. The same seems to hold for an approach based on tielines, only adding the extra effort of acquiring the tielines. In both cases, however, unrectified images have to be mosaicked and therefore an expensive iterative trial-and-error process is required to produce photographic paper prints appropriate for mosaicking.

The numerical adjustment of the radar block that is presented in this paper required less than 1 per cent of the total mapping expense. This had to be spent for measurements and data processing, but resulted in exact prescriptions to the operator of the image correlator and to the photographic laboratory for rectification of the images. This permitted saving the expense of an iterative trial-and-error process that would have been required had no numerical adjustment been carried out. We believe that the savings outweigh the investment in the numerical method and conclude that the presented numerical approach to mosaicking is not only more accurate, but could well be even less expensive than the method employing tielines.

The SHORAN-based radar mosaicking method remains, then, as the only one to require sizeable additional expenses. In the present case this would perhaps have amounted to a maximum of 15 per cent of the total mapping effort. We believe, however, that this would not have permitted us to achieve an accuracy and convenience of mosaicking as good as we could with the block adjustment method.

Conclusions

A side-looking radar mosaicking experiment was based on 24 strips of overlapping synthetic aperture radar images of an area in excess of 90,000 km^2.

The analysis of the distribution of ground control points suggests that for the sequential numerical adjustment method a regular point distribution results in the smallest mosaicking errors. If control is available only along the perimeter of the mapping area, then we conclude that the points should preferably be aligned in the flight direction.

We believe that we have demonstrated that a numerical radar block adjustment carried out prior to mosaic compilation produces results superior to an approach based merely on tielines. The overall mosaicking accuracy achieved can be represented by RMS residual errors of about $\pm$ 100 m in the flight direction, and $\pm$ 130 m across the flight direction. This coordinate direction is less accurate due to neglected effects of topographic relief.

The Schuler-periodic errors of the inertial navigation that were found in this radar survey represent the worst case yet encountered with the particular equipment used. As a result, the usefulness of the numerical method could be demonstrated with more power than if everything had been working well during the survey flight.

We find, thus, that a numerical approach to radar mosaicking produces a gain in accuracy and ease of mosaic compilation that should justify the modest investment required to take measurements and process them digitally.

References

DBA Systems (1974) "Research Studies and Investigations for Radar Control Extensions", DBA Systems Inc., P.O. Drawer 550, Melbourne, Florida; Defense Documentation Center Report No. 5307842

Leberl, F. (1975a) "Radargrammetric Point Determination PRORADAM", *Bildmessung und Luftbildwesen,* Vol. 43, No. 1

Leberl, F. (1975b) "Sequential and Simultaneous SLAR Block Adjustment", *Photogrammetria,* Vol 31

Leberl, F. (1975c) "Photogrammetric Interpolation", *Photogrammetric Engineering and Remote Sensing,* Vol. 41, No. 5

Peterson R. K. (1976) "Radar Correlator Geometric Control", Presented Paper, 13th Congress of the International Society for Photogrammetry, Comm. 3, Helsinki, Finland; Goodyear Aerospace Report GIB 9397, Litchfield Park, Arizona.

Roessel, J. van, and R. de Godoy (1974) "SLAR

Mosaics for Project RADAM", *Photogrammetric Engineering*, Vol. 40, No. 5

Schut, G. H. (1970) "External Adjustment of Planimetry", *Photogrammetric Engineering*, Vol. 36, No. 9

Yoritomo, K. (1972) "Methods and Instruments for the Restitution of Radar Pictures", Archives of the International Society for Photogrammetry, Invited Paper, Commission 2, 12th Congress, Ottawa, Canada.