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Combined Restitution of Air and Satellite Photos for Topo Maps*

Satellite imagery at 1:2,000,000 can be used economically along with aerial photos to compile 1:50,000 to 1:100,000 maps in developing areas.

Abstract: *Topographic mapping especially for the needs of developing countries could be rationalized by the incorporation of satellite photographs. These considerations are mainly concerned with map scales between 1:50,000 and 1:100,000. The satellite photographs are used both for bridging and for supplying the geometric information for topographic mapping. For topographic photointerpretation aerial photographs are used at picture scales between 1:50,000 and 1:100,000. For the combined restitution of the two kinds of pictures a new procedure has been developed. For this purpose satellite photographs and aerial photographs are coordinated in a rectifier. Thereby the previously rectified and greatly enlarged satellite photographs serve as base for the following rectification of the individual aerial photographs and for their compilation into a mosaic. This controlled mosaic of aerial photographs can serve as a base for further cartographic amendments or for the derivation of a line map.*

Introduction

Great efforts have been made in recent time in topographic mapping. Nevertheless there still exists a great shortage of topographic maps in developing countries. It is hoped that a solution of the problem might come from systematic coverage of the continents by satellite photographs. But it ought to be remembered that at present it is no serious problem to cover a vast area by aerial photographs, and most countries are already covered by pictures at scales of about 1:60,000 or even larger[1]. This means that the shortage of topographic maps cannot be overcome by the mere supplying of suitable photographs; the new medium must bring about a reduction of cost and labor in the restitution of the photographs and the compilation of the map. As many operations in the restitution process are proportional to the number of models, a certain reduction of cost automatically results from the use of satellite photographs with picture scales of 1:500,000 or even smaller, instead of aerial photographs with picture scales of 1:60,000. This gain is quickly lost if the topographic photointerpretation is handicapped by interpretation errors caused by the extremely small scale of the satellite photographs, or if completion in the field must be extended to overcome these errors.

This raises the question of what actually determines the scale of aerial photographs for topographic mapping. Limiting factors include technical restrictions as well as the requirements of image quality and measuring accuracy in the photographs. The ceiling of survey airplanes lies close to 40,000 feet. In combination with a super-wide angle camera (c = 88.5 mm) picture scales of 1:120,000 to 1:150,000 can be reached. In extreme cases even higher flying heights have been used

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for survey missions. The picture scales used for topographic mapping are much larger, in order to guarantee sufficient interpretability of the photographs[2]. Experimental studies of Neumair[3,4] have shown that under optimum conditions the picture scale can be as small as 1:120,000 for a topographic map 1:100,000, but in general the picture scale should not exceed 1:60,000. For routine work the picture scale is rarely chosen smaller than 1:50,000 for mapping 1:40,000 to 1:75,000[5].

Recent studies dealing with the restitution of satellite photographs[6] have experimented with picture scales as small as 1:400,000 for mapping in 1:24,000. The report does not give any figures of the amount by which the interpretability is reduced or of how many topographic objects are omitted by this extreme picture scale. On the other hand even with a picture scale of 1:400,000 the geometric information is not yet fully exploited. To meet the accuracy specifications in planimetry of a topographic map at 1:50,000 to 1:100,000, photographs in 1:2M to 1:3 M (*M indicates Million*) would be sufficient as will be shown later. It is therefore recommended that the picture scale not be reduced to a value which can hardly meet the requirements, but to aim at a combined restitution of aerial and satellite photographs. In this application the advantages of *aerial photographs* for the interpretability are combined with a great area of coverage. The idea of combining two survey missions of aerial photographs is not new and has been applied earlier in photogrammetry[7]. Here the large-scale photographs, i.e., 1:15,000, were used for plotting whereas the small-scale photographs, i.e., 1:60,000, served for aerotriangulation.

The concept of combined restitution of aerial and satellite photographs is similar; but difficulties must be expected as a scale difference of 1:40 or even more must be overcome. According to the practice of survey missions involving two different scales, the satellite photographs serve for aerotriangulation and supply the geometric information for the topographic map. The aerial photographs supply the image information. For the coordination of the two information carriers, it is recommended combining the two pictures in a rectifier. In this instance, the satellite photographs that are rectified beforehand serve as the base for the subsequent rectification of the aerial photographs. The resulting controlled mosaic can be used as a base for the derivation of a line map or can be published as a photo-map after cartographic editing. It is pointed out that the satellite pictures supply only information on planimetry. If these pictures would also be used for the determination of control points for heights, a much larger picture scale would be necessary as is discussed in more detail later. Otherwise efficient airborne instruments like APR or laser altimeters exist which could supply the height control by which the aerial photographs can be orientated for contouring.

For practical investigations and testing, two test fields were prepared. One of these lay in Saudi Arabia close to Medina, the other in Libya near Tripoli. In both instances the area was covered by aerial and satellite photographs: the satellite pictures were taken on the Gemini and Apollo missions with an approximate picture scale of 1:2.5 M (camera: Hasselblad 500 EL, equipped with Planar 1:2.8, f = 80 mm). The aerial photographs were taken by super-wide angle cameras, picture scale approximately 1:60,000.

It is first shown in this paper how aerial and satellite photographs can be combined for subsequent map compilation. The second part gives an analysis of the geometric information of the satellite photographs and the accuracy of a mosaic controlled by satellite photographs. Finally an integral mapping system is developed, which is based on the concept of combined restitution of aerial and satellite photographs.

Combination of Aerial and Satellite Photographs

In photogrammetry stereoscopic vision is normally used for the coordination of photographic images. Due to the great scale difference, this method could not be applied to the aerial and satellite photographs. If the satellite photographs are greatly enlarged to correspond to the scale of the aerial photographs, the differences in image quality are too extreme. If the aerial photographs are reduced to the scale of the satellite photographs, the picture size diminishes from 23 × 23 cm² to 5 × 5 mm². The small area available for stereoscopic fusion and the differences in image quality still prevented stereovision. Coordination was tried with the help of well identified *points* and by area picture coordination.

For the test with transfer points, suitable points have to be selected with a stereoscope. It proved useful to reproduce the corresponding pictures optically or photographically so that both images are represented at the same scale and can be observed binocularly. Although no stereovision is gained, it facilitates the selection of corresponding points if the surrounding area can be incorporated. The chosen points are marked by circles only on the aerial photographs; the selection of one point took about 10 minutes. Huge boulders, groups of trees or outstanding plots have been chosen as transfer points (Figure 1). It should be noticed that most of the suitable objects are not shown on small-scale maps. For this reason it causes great difficulties if corresponding points should be selected on a topographic map and a satellite photograph.

The measurement of points on the satellite photographs was performed in a stereocomparator. For this task it is recommended observing the respective area in the aerial photograph together with the corresponding section in the satellite photograph to allow optimal point setting. From repeated measurements a root-mean-square error of the

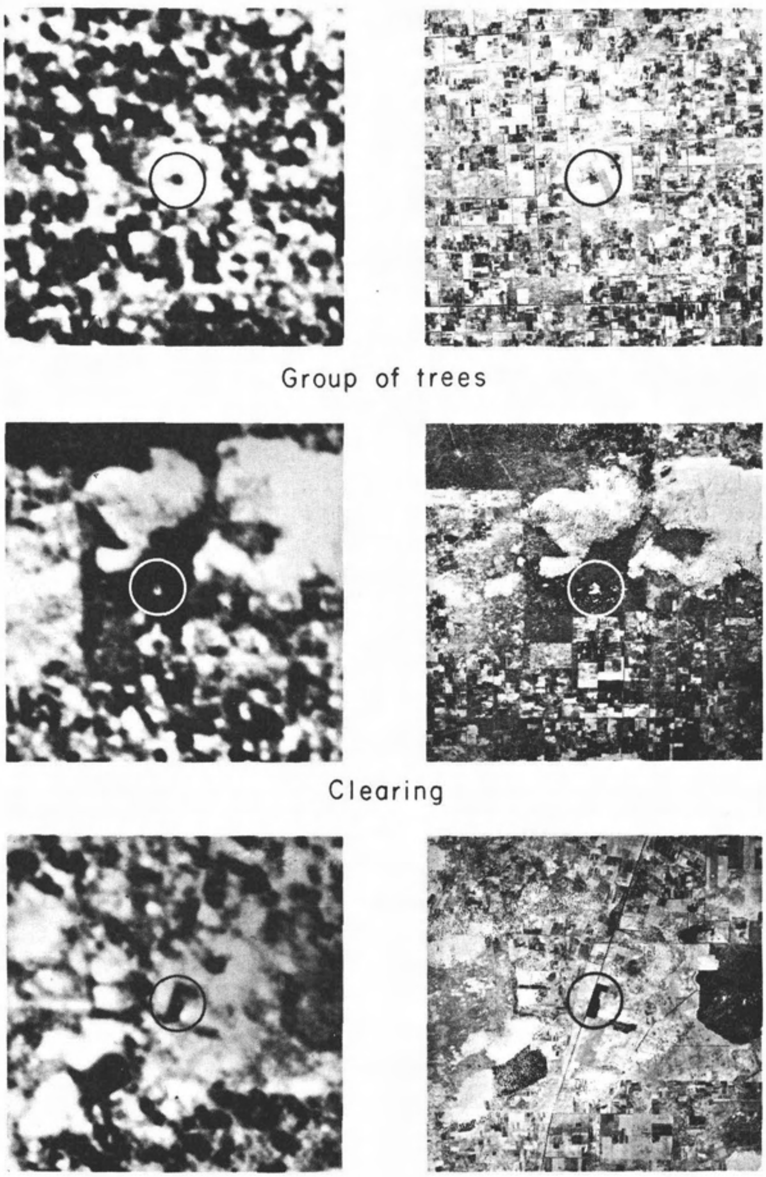

FIG. 1. Selection of measuring points in aerial and satellite photographs. The figure shows corresponding sections at the scale 1:200,000 of satellite photographs, original scale 1:2.5 M, and aerial photographs, scale 1:67,000.

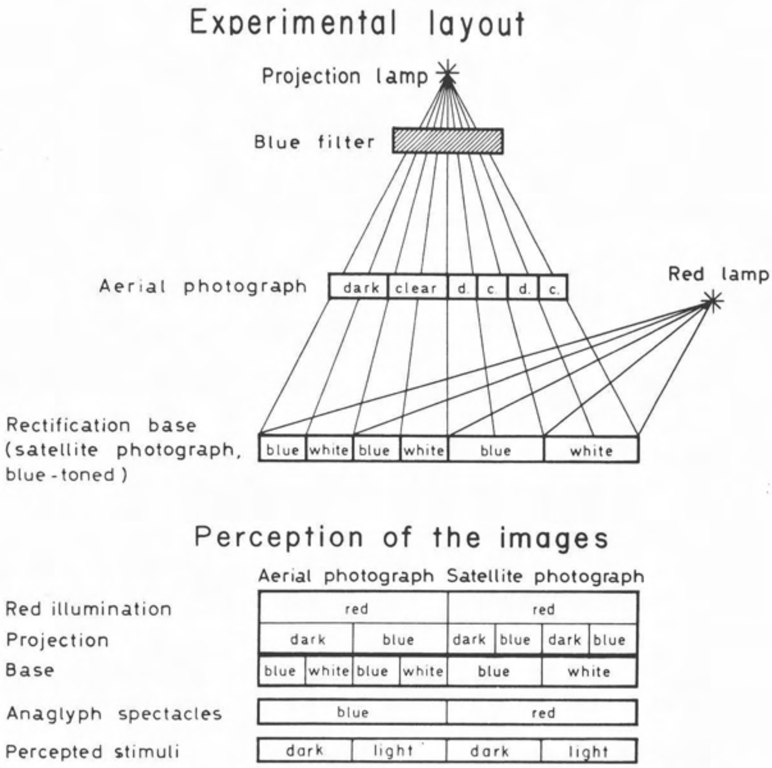

FIG. 2. Perception of images by coordination of aerial and satellite photographs. The blue-toned satellite photograph, on which the aerial photograph is projected in a blue color, serves as base for the rectification. The rectification base is illuminated by a lateral red lamp. Through the blue glass of the spectacles only the projection can be seen, whereas the red light of the lateral light source is absorbed. The rectification base, serving as the projection screen, does not disturb the projection, which has the same color as the base. On the other hand the blue projection cannot be seen through the red glass of the spectacles. Only the blue-toned satellite photograph illuminated by a red lamp is visible.

pointing precision of 6 μm was determined. Although this accuracy is relatively high the method cannot be recommended for routine work. The selection and measurement of control points for every individual aerial photograph would greatly diminish the advantages gained by the use of satellite photographs for bridging. Further, it occasionally proved impossible to find at least four transfer points, which would be necessary for the orientation of an aerial photograph, although enough details existed which could be identified on the two pictures; but their size or shape were not favorable to be used as transfer points. A suitable detail should be circular, at high contrast with its surroundings; further its size should not be much larger than the floating mark in the measuring instrument.

For the above mentioned reason, a method of picture coordination was tried which would make better use of the image information. It is not recommended to observe the pictures side by side, and not to compare the picture elements mentally. It is better to superimpose the two pictures and control in this way the coordination of aerial and satellite photographs. Special precautions are neeessary in this practice to perceive the two images separately. A similar problem arises if the two projections in a double-projector have to be separated. For this task the anaglyph principle is in general used. In a similar way the projection in the rectifier can be separated from the rectification base. Then only slight modifications are needed as a transparent picture should be matched with an opaque one.

If the aerial photograph is projected through a blue filter, the projection is not disturbed if the projection plane is white or toned blue. The same holds for a blue colored drawing against a white background, but this drawing will not be visible in the blue light of the projection. So that the drawing can be seen, an additional light source must be used to illuminate the drawing. The color of this light should be complementary (red) to the color of the projection in order not to disturb the contrast of the projected image (Figure 2). The selected colors, blue for the projection and red for the additional light source, proved very useful for practical work, but in principle any other combination of complementary colors can be used.

For the observation of the two images, anaglyph spectacles can be used. Here only one of the two images is observed by one eye. The top of a pencil or a light dot can serve as reference between the two optically separated images, similar to the scanning technique in double projectors (Gamble-plotter, Zeiss-DP 1). It is also possible to work without the spectacles. Then for the coordination of the images the operator controls the color-edge of details having high contrast.

The method has been tested with the Zeiss rectifier SEG V. Black-and-white transparencies of the aerial photographs were projected through a light-blue filter. The approximately 50-times enlarged satellite photograph served as rectification base. Actually there was no difficulty in controlling the coincidence of aerial and satellite photographs as sufficient details were readily available.

A figure for the precision of the picture coordination in the rectifier was derived out of repeated settings. This test was performed with four aerial photographs and the corresponding satellite picture. In order to control the coincidence of the picture elements on an area section of a certain size, the aerial photographs were rectified approximately beforehand. The coordination of the pictures was achieved only by shifting the rectification base (satellite photograph). The amount of the displacement could be read on scales. From a total of 64 settings with 3 repetitions, a mean observation error of $m_x = m_y = 0.18$ *mm* was derived. One setting took about half a minute to one minute.

If the observation error is reduced to the exposure scale of the satellite photographs, a value of 3.6 μm results compared with an observation error of 6 μm for point measurement in the stereocomparator. Hence the method of area picture coordination promises a much higher precision.

Especially emphasized is the shorter time for picture coordination in the rectifier. The time consuming selection and marking of suitable pass points is also superfluous. The location of sections for picture coordination causes no difficulties, whereas the number of suitable pass points very often remains unsatisfactory. Hence a suitable method for the coordination of aerial and satellite photographs is found. Before its incorporation for topographic plotting is discussed, the geometric information of satellite photographs is analyzed.

Geometric Image Quality of Satellite Photographs

For the control of geometric information, test fields were used and (as explained in the preceding section) corresponding points were selected on satellite and aerial photographs. Consequently the terrain coordinates of these points were determined by aerotriangulation with the aerial photographs. For the adjustment of the triangulation, ground control was available. From the residuals in the pass points, a root-mean-square error in planimetry and height of 6 to 10 m resulted.

As already mentioned, the satellite photographs were taken with a Hasselblad camera without a reseau grid or other special precautions to keep the inner orientation of the camera constant. Consequently no calibration report was available and the elements of inner orientation had to be considered as unknown together with the elements of exterior orientation. For a mathematical relation between the picture coordinates and those of the test field, the projection equation of Hallert[8] was used but extended for the elements of inner orientation including the radial distortion. A subsequent polynomial adjustment should take into account remaining systematic errors like film-shrinkage, tangential lens distortion, atmospheric refraction, etc.

The resulting root-mean-square error of 10 to 18 μm is comparable with the accuracy obtained with aerial photographs[9]. According to the cited publication a root-mean-square coordinate error in planimetry of 5 to 16 μm was reached for analytical restitution of single models. The coordinate measurements were executed on precision comparators as well. Contrary to the measurements on the satellite photographs for which natural points have been used as control points, the test with the aerial photographs was performed with specially signalized points. The different quality of the control points shows up only in the different pointing precision (satellite photographs 6μm, aerial photographs 2 μm[9].

The same precision as with the satellite photographs was reached with Hasselblad pictures in laboratory tests (camera Hasselblad 500 C, with Planar lens 1:2.8, f = 80 mm). These experiments dealt with the analytical restitution of single photographs. The elements of inner orientation are determined with the adjustment. As a reference, a test field was used as well. The comparison shows that no picture errors could be detected, such as those that might be caused by peculiarities involved in the taking of the satellite photographs. Therefore satellite photographs can be used like pictures of metric cameras if a suitable restitution method is chosen.

Production of a Mosaic, Controlled by Satellite Photographs

The above experiments with picture coordination were restricted to very limited picture sections. It was intended to replace the selection of control points and their measurements in precision comparators by a more efficient method. This was realized by the picture coordination in a rectifier.

It might be feasible to perform further restitution analytically after the area picture coordination. If, for example, prick points are marked on the aerial photographs before they are introduced into the rectifier, those points can be transferred to the rectification base after the setting and their Cartesian coordinates can be measured. With further data processing in electronic computers, however, all the technical and organizational difficulties that are involved with analytical procedures would be introduced. Of practical value for the small-scale topographic mapping should be an analog procedure which, as far as possible, avoids numerical computations. Especially as the intended map scale is of interest mainly for developing countries and the procedure of map compilation should cope with the technical possibilities in these countries.

If picture coordination in the rectifier is not limited to single sections, but is extended to the whole picture, then the aerial photographs will be rectified in this way, provided that the base, which means that the satellite photograph is rectified in advance. Because of the great area capacity of a satellite photograph, many fewer pass points are required for this operation than if pass points are used for each individual aerial photograph. In the following the rectification procedure and the compilation of the mosaic are described in more detail.

After rectification, satellite pictures must be enlarged to the planned map scale. This might require an enlargement of up to 50 times. It is recommended using a black-and-white sensitive emulsion on a stable base as photo material. Afterwards the enlarged satellite photographs must be toned blue. For this process the procedure shown in Table 1 can be recommended.

The preparation of the rectification base follows the rectification of the aerial photographs. The original negatives of the aerial photographs can be used for this operation. The aerial photograph should be projected through a light-blue filter. The filter can be removed before the exposure, therefore its quality is of no importance and a thin foil can be used instead of an expensive glass filter. For the illumination of the rectification base an additional red lamp is required which is mounted at the side of the projector. With this, all preparations for the rectification of the aerial photographs are complete.

The rectification can be achieved empirically or numerically. There is no difference between the number of degrees of freedom used for the rectification with control points or with the satellite photographs, and it depends only on the instrument (rectifier with or without vanishing control) and the terrain. For the well-known special case of plane but

Table 1. Process for the Blue-Toning of Photographs

Solution A		*Solution B*	
Potassium ferricyanid	9.4 g	Ammonium Iron (III) Sulphate	10.6 g
Potassium dichromate solution 1% concentration	12.5 ml	Oxalic acid	12.5 g
Water	1 l	Water	1 l

Both solutions are mixed for use in equal parts. As the mixture is only preservable for a limited time, it is recommended that one prepare only the required quantity. In this solution the developed and fixed photographs are bathed for 3 to 5 minutes. After a short wash in water they are put in a *neutral* fixer and washed for 30 minutes. The process is suitable for pictures with normal contrast and can be performed in daylight.

inclined terrain, the aerial photograph can be transformed into an orthogonal projection if a shift of the photograph is allowed.

The rectification with satellite photographs is slightly more time consuming than by the use of control points. Therefore it is recommended that one perform the picture coordination beforehand for single sections, preferably close to the corners of the aerial photographs. After the coordination of one individual section, a well-identified point on the aerial photograph is selected (for example the fiducial marks) and its projection onto the base is marked. The setting of the orientation elements is then controlled only by these transfer points. At the end of the orientation the coincidence of the two photographs should be checked again and if necessary the whole procedure is repeated.

This procedure also permits correction of systematic errors. Due to errors inherent in the satellite photographs, the rectification will only approximate the geometry of a map. The errors will be of an irregular nature like film shrinkage, and also observational errors of a systematic nature caused by the earth curvature, height differences in the terrain, atmospheric refraction or lens distortion. An estimation of the size of these errors shows that the earth curvature, as well as the lens distortion of the Planar 1:2.8, f = 80 mm, cannot be neglected. With a suitable distribution of errors the residuals might amount up to a few tenths of a millimeter at the original scale of the satellite photographs; that is, a few millimeters in the enlargements. (For a detailed study of the influence of the systematic errors see Reference 10). The size of these projection errors can be computed from the flying height, the tilt and the location of the point of interest in the photograph, together with the data of the calibration report. As these parameters are in general available, the deviation of the rectified satellite photograph from the map projection system can be taken into account at the *subsequent rectification of the aerial photographs*. For this purpose the transfer points that were advisedly marked on the rectification base are displaced by the amount of the projection error before the aerial photographs are rectified. In this way it can be avoided that systematic errors of the satellite photographs be transferred onto the mosaic of the aerial photographs.

For the *compilation* of the mosaic of rectified photographs a reference is needed! Normally this is achieved with the control points which had served before for the rectification. In the present case control points were only necessary for the rectification of the satellite photographs, the rectification of the aerial photographs was achieved without these points. Therefore it is recommended using a grid for the compilation. Such a grid should be already exposed on the rectified satellite photograph. After orientation of the aerial photographs, a highly transparent foil with thin grid lines is put on the easel and the foil is shifted in order to orient it according to the grid of the satellite photographs. For the correction of the already mentioned systematic errors, the two grids will not coincide in general. The necessary displacement can be computed beforehand. After the grid is put in its proper position, it is exposed, together with the projection of the aerial photograph, and serves for the assembling of the mosaic.

The *amount of time* for the rectification of an aerial photograph with the help of a satellite photograph is slightly higher than by the use of control points. This is caused by the area picture coordination. According to the experiments performed the additional time required lies between 5 and 10 minutes per photograph.

The precision of a mosaic controlled by satellite photographs was analyzed with photographs of Tripoli and Medina. Two strips of aerial photographs were available from the test area at Tripoli with a lateral overlap of about 50 percent. As a rectification base, a satellite photograph was taken which had been rectified and enlarged to the scale 1:50,000. The control points, which had been marked for the triangulation on the aerial photographs, were only used as check points. After the compilation of the mosaic the coordinates of the check points (a total of 46) were measured and compared with the values determined by aerotriangulation. In this way a root-mean-square error in planimetry of 0.8 mm in the scale of the mosaic was determined. The size of the mosaic was 40 × 50 cm and included 6 aerial photographs.

Another experiment with a single aerial photograph rectified by the satellite photograph of Medina gave a mean point error of 0.6 mm.

The precision obtained with these experiments corresponds to the precision obtained if control points are used for the rectification. According to a survey[11], for routine work with controlled mosaics at scales of 1:5,000 and 1:25,000, a root-mean-square error in planimetry of 0.6 to 0.9 mm was reached. Therefore the precision that was obtained by the use of satellite photographs must be considered as completely satisfactory.

It might be interesting in this connexion to consider what maximum scale ratio can be bridged by the method of the area picture coordination. On the one hand, this ratio is of course limited by the geometric information. But on the other hand this is a question of the available picture information. As already explained, well defined *areas* are used for the picture coordination in the rectifier. It is then of importance that sufficient details are present in the area of consideration. It is impossible to give figures for the number of details found in an aerial photograph, as this depends on the region, the image quality, atmospheric conditions, etc. In practical experiments a scale difference between satellite photographs and aerial photographs of 1:40 was overcome without difficulty. Another experiment failed where it was tried to match aerial photographs of the scale 1:15,000 with the satellite photographs 1:2.5 M, although corresponding details could be made out in both pictures. Nevertheless the process of coordination was too uncertain in very limited corresponding areas. The aerial photographs at a scale of 1:15,000 with original picture format 23 × 23 cm² cover an area of only 1.4 × 1.4 mm² in the satellite photograph. According to these limited experiments, picture coordination should be feasible up to at least a scale ratio of 1:50 as far as picture information is concerned, as well as for geometric information.

Proposal for an Integrated Mapping System

Small-scale topographic mapping is of special interest for developing countries. In industrial countries, base maps are in general available at scales between 1:5,000 to 1:25,000 (Germany 1:5,000, Netherlands 1:10,000, Sweden 1:10,000). Smaller map scales are derived from the base maps without additional surveys. But a great need exists for primary mapping at scales between 1:50,000 to 1:200,000 in developing countries to supply the urgently required maps for their economic development.

A proposal for the application of a combined restitution of aerial and satellite photographs must take into account the present geodetic surveys of these countries. The accuracy specification should meet the minimum requirements and be adequate for the first economic development phase of a country. After a few years these maps might no longer fulfill the requirements. But at that time they will be out of date due to the development achieved meanwhile and a new survey will be necessary[12]. Although it seems difficult to give generally accepted tolerances, the further discussion is based on an admissible root-mean-square error in planimetry of 1 mm in the map scale and 3 to 5 m in height (NATO specifications[13]).

In the following, the sequence of operations are discussed for a mapping system, based on the suggested combined restitution (Figure 3). The first phase deals with the determination of minor control points by block triangulation for the rectification of the individual satellite photographs. The satellite photographs are used for this purpose. The picture scale depends on the accuracy

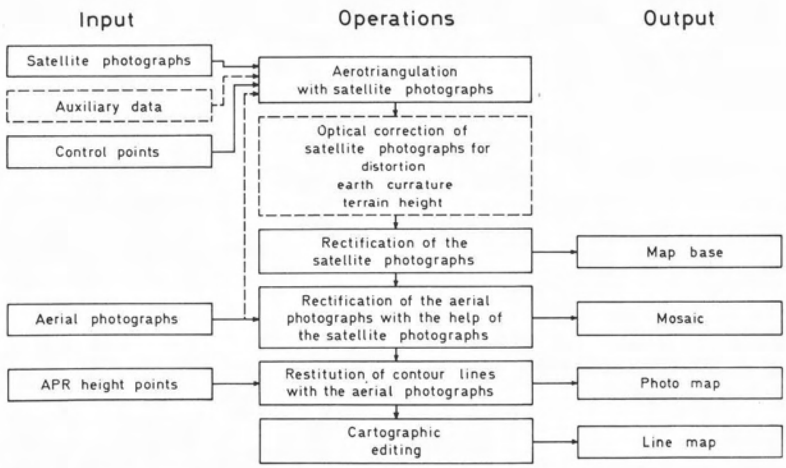

FIG. 3. Sequence of operations by combined restitution of aerial and satellite photographs for topographic mapping. (Dashed lines indicate that these operations could be omitted).

specifications and might be limited by the maximum admissible scale ratio between satellite and aerial photographs. According to the investigation into the measuring accuracy of satellite photographs, the same accuracy can be accepted as with aerial photographs. Therefore the various experiments with aerotriangulation can be transferred with certain precautions to a block of satellite photographs. According to Reference 14, in a block of 10 strips with 18 models and control points, only in the four corners is a maximum error in planimetry of $4\sigma_0$ to be expected (σ_0 characterizes the measuring accuracy in a single model). If σ_0 is 10 μm there would result a root-mean-square error in the block of 40 μm (or 100 m) for a picture scale of 1:2.5 M. As well as using a larger picture scale, the accuracy could be raised by the incorporation of auxiliary data[15] or the use of more control points.

It should be noticed that the assumed block size of 10 strips with 18 models covers an area of 1000 × 1000 km if satellite pictures of scale 1:2.5 M in Hasselblad format (55 × 55 mm^2) are used. In comparison, the coverage of the same area with aerial photographs with a picture scale of 1:60,000 (picture size 23 × 23 cm) would require the triangulation of about 18,000 models. With a smaller number of models for aerial triangulation, the amount of time and the cost of this operation decreases proportionally. This means that the cost of determining the minor control points can be reduced up to one hundredth of the original cost by the incorporation of satellite photographs.

After aerotriangulation with the satellite photographs, these photographs are rectified, toned blue, and serve as a base for the rectification of the aerial photographs. To guarantee sufficient interpretability, the picture scale should not exceed 1:60,000 to 1:100,000 as already discussed earlier.

The mosaic compiled from aerial photographs can serve as base for the derivation of a line map, or be published as a photo map after cartographic editing. As well as the planimetry, the representation of the relief is an integral part of a topographic map. The determination of heights was not included in the aerotriangulation as the requirements cannot be met by the chosen picture scale. This seems reasonable as efficient non-photogrammetric survey methods exist (like airborne profile recorders [laser altimeters] and statoscopes) for determining of the necessary height control. The aerial photographs are orientated with these control points for the plotting of the contour lines. As the rectified photographs can be used for the plotting, approximate instruments like Stereotop or Stereomicrometer would be suitable for the restitution of the pictures.

It should be possible to meet the prescribed height specification in this way. According to Reference 16, a height precision of 1 to 2 m can be reached with the laser altimeter after suitable adjustment of the height profiles. The root-mean-square error for contouring in approximate instruments is indicated as 0.4 percent of the flying height[17] (corresponding to 2.5 m for 6,000 m flying height, c = 88 mm). With a total height error of 3 to 4 m, a satisfactory result is obtained.

In this way it is possible to produce a map at scales of 1:50,000 to 1:100,000 in a relatively short time. Apart from the aerotriangulation, no operations require specially qualified personal or sophisticated technical equipment.

The author hopes that this paper contributes to finding a solution for a very urgent problem of the developing countries.

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Abbreviations:

OEEPE: European Organization for Experimental Photogrammetric Research
IAfPhm: International Archive for Photogrammetry
Phm. Eng.: Photogrammetric Engineering
DGK: Publication of the Deutsche Geodätische Kommission
BUL: *Bildmessung und Luftbildwesen.*

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