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PERFORMANCE AND DEVELOPMENT OF AERIAL TRIANGULATION FOR MAPPING

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1. The present status of aerial triangulation

1.1 This is a review paper on aerial triangulation. Its main intention is a summary of the technical status which aerial triangulation has reached, in particular with regard to its application for topographic mapping. Also, some current developments are discussed which still further increase efficiency and performance.

As the details of the development are hidden and spread in numerous scientific papers this presentation attempts to summarize and to venture an evaluation of the status reached. It also points to the strategies to be pursued for providing control for photogrammetric mapping.

This paper also contains the experience of the author in the field of aerial triangulation, derived from the development and application of the Stuttgart computer programs. But it is valid in a much more general way, attempting to embrace the development to the total field.

The limited space available prevents the elaborate presentation and documentation of technical details. References and complete documentation may be requested from the author.

1.2 Photogrammetric mapping still requires control for the absolute orientation of photo-pairs. As geodetic control is often not available at all or not in sufficient density nor at the required location it has been the standard task of aerial triangulation to provide such control, previously referred to as minor control.

Modern aerial triangulation has greatly reduced the requirements for geodetic control. Nevertheless some given control points are still necessary. Thus, aerial triangulation is in principle a method for network densification by photogrammetric means.

The network-densification aspect of aerial triangulation has been greatly promoted recently by its increased accuracy performance such that it became self consistent and feasible for purely geodetic application. Densification of lower order geodetic networks by aerial triangulation is being applied, often in connection with photogrammetric cadastral surveys. The combination of network densification and cadastral surveys has become highly effective, jumping over some steps of the classical hierarchy of networks. A special case is the photogrammetric determination or reference points in the terrain for further use by local ground surveys.

Hereafter we shall only discuss the application of aerial triangulation to the classical problem of providing control for topographic mapping at medium and small scales which is world-wide the task of national mapping.

The transition of aerial triangulation to blocktriangulation, combined with computational least squares adjustment, has pushed the performance on a new level. The accuracy results have been improved by about a factor of 20 or more. Part of it is due to improved hardware (cameras, films, measuring equipment). But most of the improvement is attributed to the progress achieved by numerical methods of simultaneous and rather rigorous least squares adjustment.

1.3 About 15 years ago theoretical accuracy studies suggested a very high accuracy potential of photogrammetric blocks. They also showed how the essential planning parameters, such as block-size, overlap, control distribution etc., would influence the results.

With regard to planimetry it became evident that planimetric control points are primarily required along the perimeter of a block. Of course, when additional control inside the block is available, it would be used, but complete perimeter control would still be essential.

With dense perimeter control (control points only 2 or 3 base lengths apart) blocks have particularly good accuracy features with regard to planimetry: (a) The average accuracy is quite uniform within a block. (b) The average accuracy of blocks is only very little dependent on block size and on block shape. (c) The average accuracy of such blocks remains very close to the precision level of the measurements. In other words the planimetric accuracy of blocks of any size is nearly the same as that of fully controlled individual models.

The theoretical investigations suggested two important conclusions: First, aerial triangulation could be extended to large or even to very large blocks (in the order of 1000 photographs per block or more), without requiring planimetric control points inside the block area. The anticipated impact on blocks for small scale topographic mapping was obvious, as with large blocks relatively fewer control points would be required.

The second conclusion, equally revolutionary, showed the potential of high accuracy aerial triangulation to be applied with large scale photography. Large photo scales (around 1 : 5000) give measuring accuracy in the order of a few cm in the terrain. It could be expected to reach such accuracies also with blocks.

Both extensions of aerial triangulation - large blocks for small scale mapping and high accuracy point determination with large photo scales - have been realized and applied most successfully in the meantime. Although based on simplified theoretical error assumptions the conclusions proved to a great extent valid in practical application.

1.4 With regard to the vertical accuracy of blocks the theoretical investigations did not give results as revolutionary as for planimetry. It was confirmed that blocks with 20% side overlap of strips - still the standard case - require chains of vertical control points which run across the block, in particular also across the inside area of a block. Within each chain vertical control points should be only 2 base lengths apart and should be located in or very near the lateral overlap areas of adjacent strips. The final vertical accuracy of a block depends mainly on and deteriorates with the "bridging distance" which is the distance between the chains of vertical control. The accuracy is independent on block size provided that additional chains of vertical control are added in order to keep the distances between them at a prefixed more or less constant value.

However, for short bridging distances (3-5 base lengths) the vertical accuracy of adjusted blocks, as well as of individual strips, remains in the same order as the vertical accuracy of fully controlled individual models. This property allowed the same conclusion as for planimetry with regard to high accuracy aerial triangulation with large photo scales. The expectations have proven valid in applications for large scale engineering work or for large scale mapping with contour intervals of 1 m or even 0.5 m.

For small scale mapping, however, bridging of very large distances of perhaps 100 km or more without vertical control seemed not permissible, because of the high vertical accuracy often required in small scale mapping, when specified contour intervals are 50 m, 20 m, or even 10 m in flat areas.

Fortunately, this problem found a most effective solution by relying on vertical auxiliary data as they are provided during the flight missions by statoscopes or airborne profile recorders (APR). The statoscope is a sensitive differential barometer which provides information about the z-coordinates of the camera stations, referring however to an unknown isobaric surface in the atmosphere as reference. If the isobaric reference surface is adequately taken into account by additional unknown orientation parameters the joint adjustment of photogrammetric blocks and statoscope data yields vertical accuracies of the adjusted blocks in the order of 1 m (or 2 m with high altitude photography), for bridging distances up to 200 km or more. The same holds for APR data which are also hooked on barometric measurements.

The statoscope is a particularly simple and inexpensive instrument. It is highly recommended to be used all the time in medium or small scale flight missions. Its value in terms of saving vertical ground control is most remarkable, as only vertical control at either side of a block is required (which can still be further reduced by flying cross strips). It can be said that the statoscope has one of the highest cost-benefit effects we know of in photogrammetry.

As result it can be stated that with auxiliary data very large blocks are feasible without vertical control inside the area. The required contouring accuracy can be safely obtained for all cases of medium and small scale topographic mapping, down to contour intervals of 20 m or 10 m.

1.5 The theoretical accuracy potential of blocks motivated the development of universal computer programs for block adjustment. A number of such programs has been realized in the meantime which can handle practically any size, shape, and overlap of blocks as well as any number of control points and tie points. They also handle the organisation and management of the great number of observation data automatically.

The numerical problems which had to be solved were quite severe. It suffices here to mention only that

- the adjustment systems are very large; the number of unknowns runs up to the order of 10^4 or more
- the adjustment systems are non-linear; which asks for automatic determination of approximate values for linearisation and iterative solutions
- the data handling has to be automatic, including automatic search for overlaps, tie points, control points and procedures for optimisation of the computing process (such as minimum bandwidth, for example).

The first programs realized were adapted to large main frame computers. As even their core memory capacity was by far not sufficient algorithms for effective combination of internal and external memories were required in order to keep the computing times short and to adapt the programs to various computers.

In the meantime the computer development made it possible to transfer such programs to mini-computers, still in general form, without any restrictions. More recently, block adjustment programs have been implemented on analytical plotters, although with some restrictions as to the acceptable size of blocks.

Today highly efficient and general computer programs for block adjustment are available which are easy to transfer and which can be operated anywhere. Their high level of automation makes operation relatively easy, and they can cope with almost any case of block adjustment which may occur.

It is well known that there are two main methods of block adjustment in current use, known as the independent model method and the bundle method. Polynomial methods of adjustment are being abandoned.

It is not the place here to analyze and compare the two methods. It may suffice to say that we consider the independent model method as the working horse for aerial triangulation. The bundle method, somewhat more rigorous, fully analytical and therefore more specific with regard to input requirements, displays its potential mainly in the field of high precision aerial triangulation.

In the following chapter a few items are discussed in more detail, especially in view of their relevance for the planning of mapping projects.

2. Some special considerations about aerial triangulation for mapping projects

2.1 In view of the high accuracy performance of block adjustment it should not be overlooked that the precision level of the measurements which serve as input data for the adjustment is quite decisive for the accuracy of the end result. Input data are pre-corrected plate coordinates (x, y; for bundle method), model coordinates (X,Y,Z; for the independent model method; obtained from analogue instruments after relative orientation or by analytical relative orientation from plate coordinates), ground control points, and auxiliary data. They determine the resulting accuracy of the adjusted block, together with the geometrical structure given by overlap, tie connections and control points.

Because of the great number of observations involved the photogrammetric measurements determine the precision level in first instance. It is expressed in the adjustment by the σ_o-values, known as "standard error of unit weight" or "reference standard deviation".

There are several levels of σ_o-values to be distinguished, depending on the main source of errors contained in the observations. Table 1 summarizes our experience (including the results of adjustment with additional parameters which will be discussed in chapter 3).

In conventional aerial triangulation, as it is used for mapping projects, the transfer and artificial marking of tie points determine mainly the precision level of the input data, quite independent of the actual measurements. Referring to the photo-scale, σ_o-values used to range between 15 and 30 µm, up to 40 µm or more. Recently σ_o-values below 10 µm have been obtained, with latest equipment for point marking and point transfer.

When signalized tie points (and control points) are used, for instance in cadastral application, the instrumental errors of analogue instruments constitute the main source of errors, reflected in σ_o-values of 8 - 12 µm. If the instrumental errors of analogue instruments are eliminated by using mono- or stereo-comparators or analytical plotters the σ_o-values go back to 4 - 9 µm and 3 - 8 µm for analytical independent models and bundle adjustment, respectively.

The remaining errors are primarily attributed to remaining unknown systematic image errors which are not caught by the conventional pre-correction of known systematic errors, such as refraction and lens distortion. Such unknown systematic image errors can be dealt with and corrected for (to some extent, depending on overlap, number of tie points and on control) by introducing additional unknown parameters into the block adjustment. The method is known as self calibration or adjustment with additional parameters. The resulting elimination of unknown systematic image errors leads to σ_o-values of 2 - 5 µm. They demonstrate the extreme accuracy which photogrammetric point determination is capable of.

Scientific literature, pursuing the highest possible accuracy, has been concentrating during the past few years on the method of additional parameters. But it should be kept in mind that most published results refer to the case of signalized tie points. This is, however, still an exceptional case and should not be misunderstood as representing the great majority of practical application of aerial triangulation. In mapping projects the artificial marking and transfer of tie points is still standard. The conclusion therefore is that in practice every effort should be made to stabilize the precision of point transfer on the 10 µm or 15 µm level, in order to ensure predictable high quality performance of aerial triangulation for mapping projects.

Table 1 Empirical magnitude and range of σ_o-values in aerial triangulation for various cases

case	type of tie-points	measuring instrument	method of blockad-justment	$\sigma_o^{x,y}$ in photo scale	major source of errors
1	artificially marked points (conventional)	analogue instr. or comparator	indep. model adjustment or bundle adj.	15 - 40 µm	point transfer
2	signalized points	analogue instrument	indep. model adjustment or bundle adj.	8 - 12 µm [1)]	instrument errors
3	signalized points	comparator or analytical plotter	indep. model adjustment 2)	4 - 9 µm	systematic errors
4	artificially marked points (latest results)	comparator	bundle adjustment	6 - 10 µm	point transfer, system. image errors
5	signalized points	comparator	bundle adjustment	3 - 8 µm	systematic image errors
6	artificially marked points (latest results)	comparator	bundle adj. with add. parameters	5 - 8 µm	random and correlated image errors + point transfer
7	signalized points	comparator	bundle adj. with add. parameters	2 - 6 µm	random and correlated image errors

1) the σ_0-values of the bundle method (referring to image coordinates) and of the independent model method (referring to model coordinates) cannot be compared directly. If the latter are derived from image coordinates by analytical orientation they are theoretically about 1,5 times larger.

2) after analytical relative orientation of stereo-pairs.

2.2 With a given precision level (σ_o) of the photogrammetric measurements the resulting accuracy of adjusted blocks is then mainly determined by their geometry, that is by overlap and control.

With dense perimeter control the average planimetric accuracy ($\mu_{x,y}$) is theoretically $\mu_{x,y} \approx \sigma_o$ for medium size blocks, going up to $\mu_{x,y} \approx 1{,}2\sigma_o$ or $1{,}3\sigma_o$ for large blocks. In practice, for project planning, it is safe to use $\mu_{x,y} \leq 2\sigma_o$ as a rule of thumb. This is particularly valid for high precision, large scale blocks.

In medium and small scale mapping projects, however, such high planimetric accuracy is not required. The photo scale to be applied is usually pre-specified not by the geometrical accuracy but by the interpretability of detail (or by the maximum obtainable altitude of the aircraft). For map scales of 1 : 50 000 or 1 : 100 000 photo scales in the range of 1 : 60 000 to 1 : 100 000 are widely used, with wide-angle or super-wide-angle cameras.

A measuring precision (σ_o) of, say, 15 μm in photographs of for instance 1 : 80 000 scale is equivalent to 1.20 m in the terrain. For a block of any size, with dense perimeter control, the average planimetric coordinate accuracy of the adjusted points could then be expected to be better than about 2 m to 2.5 m. However, the required planimetric accuracy in the map is considerably less. The graphical accuracy of 0.1 mm in a topographic map of scale 1 : 50 000 or 1 : 100 000 is equivalent to only 5 m or 10 m, respectively, in the terrain. Thus, the aerial triangulation results would be more accurate than required.

This accuracy margin is exploited economically by reducing the number of control points, in particular by using what we call relaxed perimeter control. The details have to be worked out in each particular case, according to the pre-set specifications. For topographic mapping the general result is, that relaxed perimeter control allows distances between planimetric control points along the perimeter of a block in the order of 10 or more base length, which means control only at distances of more than 50 km, up to 100 km, depending on the set accuracy specifications. Thus the total number of required planimetric control points is very much reduced, to about only 10 or less, even for very large blocks. This means that the required control points may be determined by the Doppler method, making use of the TRANSIT navigation satellites. In this way the tedious task of establishing geodetic ground control is being greatly eased.

In blocks with relaxed perimeter control the maximum standard errors are expected at the open parts of the perimeter, in between the control points, whilst the interior area of the block is little affected. The permissible maximum standard errors have to be specified and considered in proper project planning. Here a word of caution is appropriate. With dense perimeter control uncorrected systematic errors are quite effectively suppressed. But with relaxed perimeter control systematic errors show up primarily at the open perimeter and endanger the accuracy there. Thus the permissible distances between control points cannot be made as big as would be the case in the presence of random errors only. Nevertheless the control points can be located wide apart as has been shown above. There is another safeguard which is worth being mentioned. If the net area of a block is bordered by additional photography, which is utilized in the adjustment, the maximum errors along the perimeter of the net area are effectively suppressed, and the planimetric control points can be put still further apart.

For the case of relaxed perimeter control another remark is appropriate. The fewer control points are used the more they must be absolutely relied upon. Unless they are very big gross errors in widely spread control points cannot be discovered by the aerial triangulation. It is particularly important to make sure that geodetic control points are safely identified in the photographs. It is recommended, therefore, to signalize planimetric control points in the terrain, or to make them uniquely identifiable in other ways. It is also recommended to use locally pairs or triplets of control points. In this way the reliable identification of control points can be controlled whilst the additional geodetic efforts remain negligible.

2.3 The conventional vertical measuring accuracy from air photography is, for arbitrary terrain, about 15 µm in photo scale (with wide-angle photography, slightly better with super wide-angle photography). The equivalent magnitude in the terrain is 1,20 m from 1 : 80 000 scale photography. (This corresponds to σ_0 (not contained in table 1) of the separate vertical adjustment of independent models or about to the equivalent parallax accuracy, multiplied by the base/height ratio, of the bundle adjustment).

Such measuring precision propagated through the block adjustment would lead, for the large bridging distance desired in small scale aerial triangulation, to maximum standard deviations for the adjusted heights of more than 5 m up to perhaps 10 m. This result would only be acceptable for contour intervals of 50 m or larger and cannot be considered generally sufficient.

The use of statoscope- (or APR-) data, however, can keep the vertical accuracy of adjusted blocks in the order of 1 - 2 m, even for extremely large bridging distances (such as 20 - 30 base lengths or 100 - 200 km or more). It means that the requirements for contour intervals of 10 m (or even 5 m) are safely reached.

Recent investigations suggest that statoscope data are also highly effective for the mapping at larger map scales (1 : 10 000 for instance), where the required vertical accuracy is in the order of 0,5 m. Bridging distances can be extended to at least 10 base lengths or more for mapping with contour intervals of 2,5 m or 2 m.

2.4 Some adjustment programs allow the introduction of additional conditions such as water level constraints for shore lines of lakes or the sea. In case applicable the constraints are to some extent a substitute for vertical control when water surfaces are in the area or border the area.

2.5 APR equipment measures vertical terrain profiles, whether during the air survey flight mission directly or from separate low altitude flight missions. APR-data can be brought into joint block adjustment in almost the same way as statoscope data. Their error properties are also very much alike as they also contain barometric measurements and relate to an unknown isobaric reference surface in the atmosphere. Utilisation of APR data requires transfer operation into the photographs. Also the equipment is more sophisticated and, at present, not on the market anymore. As statoscope data have almost the same effect on the block adjustment as APR-data and as they can be obtained and handled in simpler ways it is normally recommendable to utilize only statoscope equipment.

APR profiles have, however, one additional advantage which can be essential in extreme cases. They allow to pick up an absolute vertical datum (from the sea, from a lake, rivers, an airport etc.) and carry it into the block area in case there is no vertical control available there at all. Some computer programs can handle such cases which occur when completely inaccessible areas are to be mapped.

2.6 Computer programs which can accept and adjust APR data together with the block adjustment offer an interesting special application the possibility of which is not yet generally known.

There are areas which are almost inaccessible for field parties, such as swamp areas. Mapping of such areas often requires high vertical accuracy, for instance for drainage planning. It can be extremely difficult and/or expensive to provide the required vertical control in the area.

In such cases one can work with photogrammetrically measured terrain profiles which are treated in the adjustment as artificial or pseudo-APR-profiles. The principle is that the heights measured photogrammetrically on stretches of visible shore lines of open water areas, canals or rivers form profiles which are either level or have constant slope. The profiles need not be straight, constant slope is the only condition. A criss-cross pattern of such profiles, which need not be interconnected, forms a substitute of vertical control. The result can be of very high accuracy, even without any vertical control inside the area.

We handled recently such a project from an African country with great success.

2.7 Those examples demonstrate that versatile adjustment programs for aerial triangulation are highly practical and economic tools. They ease the problem of geodetic control very much which used to be a bottle neck in small scale mapping.

In addition it should be mentioned that in aerial triangulation the point transfer and the measurements have become standardized to such a degree (3 - 4 photos per hour for preparation and also for measurement) that aerial triangulation is not only a highly accurate and economic procedure. It is also highly reliable and predictable in terms of accuracy, costs and time requirements. It may even be said that the predominance of the geometrical aspects requires little local knowledge about the areas in question. Therefore block triangulation can easier be contracted out than the actual mapping.

As a result aerial triangulation has developed into a most powerful and economic procedure. It is to a great extent responsible for the high performance of modern photogrammetry and has become quite indispensable. Almost all photogrammetric projects go now through the aerial triangulation stage first.

3. Remaining problems and current development

3.1 In spite of the highly satisfying results obtained by block adjustment there remain a number of practical and scientific problems which deserve further attention.

The first problem area concerns systematic image errors. It has been a prime object of development and research during about the last 10 years. It is related with the question whether the actual results of aerial triangulation match the theoretical expectation. A number of national and international tests have analyzed the problem.

The tests have confirmed on the one hand the general high accuracy performance of block triangulation. In particular well controlled blocks have proven to be in fair agreement with theoretical accuracy expectation. On the other hand, however, when looked at closer the results showed evident disagreement with prediction.

The explanation is that the theoretical accuracy expectations are based on too much simplified assumptions. They take only uncorrelated random errors into account, assume ideal geometry of blocks, and disregard systematic errors, undetected blunders, and errors in the control points. Such idealized assumptions could not be truly realistic. It was therefore no real surprise that actual blocks behaved somewhat different. The tests also showed that unknown systematic image errors, remaining after the a priori correction of known systematic errors, are the main cause of disagreement between actual results and theory. Such errors are quite small (order of magnitude 5 µm in the photograph) but they are almost always present and can propagate dangerously especially in poorly controlled blocks.

Consequently, adjusted programs were extended to cope with unknown systematic image errors by adding correction terms, the unknown parameters of which are determined by the adjustment. The method is referred to as adjustment with additional parameters or selfcalibration. Those terms are self explanatory.

In the technical solution a number of problems had to be solved, with some of them the struggle is still going on. The first question was by which and by how many terms the unknown systematic errors were to be described. Almost each author suggested a different set. Secondly the procedure has to be made automatic and safe. Additional parameters may lead to ill-conditioned or singular systems of equations. They also may be statistically insignificant. Thus algorithms and tests had to be developed which would prevent possible deterioration of results. It was further established that the extent to which unknown systematic errors can in principle be recognized and corrected depends on redundancy, especially on overlap and on number and distribution of control points and of tie points. The accuracy improvement of additional parameters is particularly good in planimetry. Vertical improvement remains moderate in blocks with only 20 % side overlap.

In spite of all difficulties, however, the effectiveness of the method has been well established. The accuracy improvement is around 30 % with well controlled blocks, it can go to 100 % and 200 % or more in poorly controlled blocks. The application of block adjustment with additional parameters is becoming standard in the field of precision, large scale point determination. On the other hand specialized expertise is still required for proper application, and the computing efforts and costs are considerably increased.

The additional parameter method has not ultimately solved the problem of a refined adjustment approach. At present scientific investigations probe into a more complete error analysis of aerial photographs, including the variation of errors and the correlation within and between photographs of a mission. It is still an open question how much additional improvement might be gained by a more sophisticated theory of errors.

3.2 Another most urgent problem is the elimination of gross data errors. In sets of thousands of observations there are always some blunders. Their magnitudes vary greatly, also their frequency (0,1 % to 1 %). Certain groups of data are especially sensitive. It is no particular exception, for instance, that 10 % or 20 % of the planimetric ground control points cannot be used. The causes are very often wrong identification or administrative (numbering) errors.

Detecting and locating gross errors in the course of adjustment is a serious problem. Its solution had conventionally been left to the human operator who tries to identify gross errors in a step by step procedure, which requires repeated or partially repeated adjustment runs (usually about 3 - 6). It is a tedious operation which requires great skill and experience.

It is therefore of greatest practical importance that algorithms are developed which can detect gross data errors automatically. The statistical theory of separating small blunders (outliers) from random errors is essentially developed. Best known is Baarda's "data snooping" method. Currently block adjustment programs are being modified to include automatic blunder detection. Particular initial difficulties are raised by very large blunders which can completely distort a block. They are attacked by "robust" adjustment methods.

The statistical theory shows that the principal possibility of blunder detection depends on (local) redundancy and geometrical strength of a block. There are lower threshold magnitudes down to which blunders can be safely detected at all. Such threshold magnitudes, which are often uncomfortably large (5 - 10 σ or larger), can be clearly established by the theory of reliability which means reliability against undiscovered gross errors.

Photogrammetric blocks have in general very good reliability, as good as geodetic networks. Nevertheless certain precautions have to be taken in order to ensure the detection of gross errors larger than the lower limit threshold, in case they occur. It is recommended, for safe blunder detection, to use always pairs of tie points and to strengthen the weak open perimeter areas of a block by additional overlap. It is further recommended to use pairs or triplets of control points, especially in case of scarce planimetric control.

Reliability (against blunders) is a separate quality of blocks or networks which is to be considered independently and in addition to accuracy. Project planning has to take care of it, in order to make sure that all blunders which would seriously disturb the adjustment results can be safely discovered.

3.3 Another current development is on-line aerial triangulation. The idea is that observations are checked by continuously updated adjustment computations during the measurement phase. The advantages are early blunder detection, early and easy remeasurement in case necessary, and prechecked data for the final adjustment. On-line methods are applicable especially with analytical plotters. Some economic savings are expected. The end results, however, can only be the same as with conventional off-line adjustment.

3.4 It has been discussed in chapter 2 that modern block adjustment has become a powerful economic tool. Especially in the application to topographic mapping it has succeeded in meeting standard accuracy specifications with greatly reduced requirements for geodetic control.

Nevertheless, providing geodetic control for small scale mapping can still be a time consuming and expensive task. The question has therefore to be asked whether the required minimum number of geodetic control points could still be further reduced or whether aerial triangulation might even be able to operate without geodetic control at all.

This problem is being studied at the author's institute. The strategy is to make use of additional auxiliary data which are becoming available by the technological development. We have already seen the great impact which statoscope- or APR-data have had on the saving of vertical control.

In a similar way direct measurement of the xy-position of camera air stations, also processed through joint block adjustment, will be highly effective. The technological progress can provide such auxiliary data in 3 ways:

- There exist systems which record permanently distance measurements from fixed or portable stations to the aircraft and thus allow continuous trilateration for the camera air stations. Although intended originally for air navigation of photo flights the data can equally be used as auxiliary camera orientation data in the block adjustment. The expected accuracy is better than 1 m, for the time being.
- Inertial navigation systems provide information about the flight path and, more specific, about the position of the camera stations. (With a third channel also vertical data are obtained. The processing however will depend on a sufficient knowledge of the local gravity field.) Although again intended for navigation purposes the data are excellent auxiliary data to be used in combination with block adjustment. The reference drift of such data has further to be taken into account by the adjustment and the error behaviour has further to be analysed. It is quite realistic, however, to expect eventual planimetric precision of the data in the order of 2 m or better over limited distances as they are given by the strip lengths of practical photo flights.
- In future, the continuous recording of satellite GPS (Global Positioning System) data during the photo flight mission will provide highly accurate information about the camera air stations in all 3 coordinates.
- Inertial platforms can also provide direct tilt data for aerial photographs. Although they are not as effective for aerial triangulation as position data they will certainly be considered too.

First computer simulations have confirmed that the joint adjustment of such auxiliary data and photogrammetric block data form a highly effective combination. The planimetric accuracy specifications for small scale mapping can certainly be met on the basis of 4 control points only in the corners of blocks of any practical size. If the absolute accuracy of such systems will be fully exploited it is feasible that small scale blocks might be handled even without any horizontal control in the area.

Thus it is to be expected that a major step is due which could make aerial triangulation for medium and small scale mapping even more effective and more independent of geodetic control as it is already now.

We hope to report on actual test results at the forthcoming Congress of ISPRS in 1984.

3.5 There are other interesting lines of development based on the philosophy of combining aerial triangulation with other tasks. The example of combining aerial triangulation with cadastral surveys has already been mentioned. In a similar way the data acquisition for digital mapping could be combined with aerial triangulation.

Here the attention is drawn to combining aerial triangulation measurements and the data processing of digital terrain models, especially of digital elevation models (DEM). Such combined projects which have been successfully applied gain importance. Digital elevation models are often an independent product in its own standing, for further application in engineering projects and in geo-science. They will be the basis for national orthophoto-maps and serve for the rectification of scanner imagery from space. They are also used for automatically deriving and plotting contour lines, thus substituting conventional contouring. The method is already competitive for large scale contouring, and will be so for small scale maps too.

The rapid transition to digital technology make digital elevation models an alternative description of the topography of a country and as such an independent product. Is it gradually understood that national mapping agencies are to produce digital elevation models and to make them available to everybody, in the same way as contour maps were made available as analogue description of the topography of a country.

By a modification of radar scanners, which would penetrate through forest cover, it is expected to obtain digital elevation data in densely forested areas. Thus it can be hoped that by the combined development of sensor technology and of digital data processing this last problem of topographic mapping could be solved.

4. Conclusion

This paper attempted to show that modern aerial triangulation has developed into a most versatile efficient basis for mapping projects. The accuracy and operational performance have made it highly economical. In particular the requirements for geodetic control have been greatly minimized to the extent that they present no obstacles any more for carrying through national mapping programs within short periods of time.

The current development is making aerial triangulation still more automated, more efficient and still easier applicable. It will succeed in reducing control requirements still further.

In the Federal Republic of Germany very considerable know-how experience is available in aerial triangulation on related fields. We can render service and offer technical cooperation for the benefit of completing the tasks of topographic mapping which many countries still have to solve.