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Aspects of Automatic Aerotriangulation

WERNER MAYR, Königsbronn

ABSTRACT

Digital images are the basis of digital photogrammetry. They allow the application of automated measurement procedures. In aerotriangulation one of the core tasks is measuring in images. The organisation of the work flow determines the efficiency of aerotriangulation. It is an advantage of digital photogrammetry that all procedural steps can be performed on the computer. Automated measurement procedures characterise automatic aerotriangulation. Several aspects of this new exciting method are discussed in this paper.

1. INTRODUCTION

Conventional aerotriangulation consists of the three steps block preparation, measurement, and block computation. This scheme is valid in automatic aerotriangulation (AAT) as well. However, AAT is based on digital images, automated measurement techniques, and an almost automated procedure. Digital images usually are generated using a photogrammetric scanner. For the automated measurement process the methods of image matching, e.g. feature based or area based matching, are applied. The automated procedure can be achieved by combining appropriate steps accordingly. Automated point measurement techniques and the automated procedure are the determining properties of AAT in comparison to conventional aerotriangulation. Bundle block adjustment is the computational principle for determining the orientation elements and the unknown object coordinates of conjugate points. AAT is a point of major interest in research and development, e.g. Ackermann 1991, Tsingas 1992, 1994, Jaakola and Sarjakoski 1994.

2. PRELIMINARY CONSIDERATIONS

The technical terms to be used in AAT are not yet decided. For this reason some definitions are included within this paper. Digital aerotriangulation is the technique to automatically measure in digital images. The procedure can further be classified in a more detailed way as automatic or manual.

2.1 Requirements

The defined task of AAT is to connect all images of an aerial image block by using automatic measurement techniques in a self-controlled way. The following input data are available:

- flight information,
  - overview map of image centres,
  - flight protocols,
- digital images with interior orientation and image pyramid levels,
- ground control point information in the form of point identification string, coordinate triplet, and ground control point sketch,
- aerial camera data,
- maps, if available.

An image block consists of several image strips, and these each consist of several images. The common case of an image block covers several strips. GPS-based (Global Positioning System) image blocks often contain cross strips along the block border. Many blocks also contain one or more strips with

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arbitrary direction. The block border is usually not a regular, rectangular shape. These and other image block configurations are to be processed by AAT.
Besides the capability to automatically measure an image block, manual measurement capability is also a requirement. In this operating mode of AAT the user can interactively measure all kinds of points. These include existing tie points, ground control points (GCPs), and new, to-be-determined object points. The interactive measurements are performed for reasons of control or additional measurements. In this context a clear advantage of digital aerotriangulation over conventional aerotriangulation has to be pointed out. In digital aerotriangulation, and especially in AAT, a GCP or new object point can be measured in more than two image windows *simultaneously*.
A characteristic of the automatic measurement technique is that it recognizes situations where it cannot perform autonomously. In such instances it guides the user to the questionable location and asks for interactive help. However, due to the enormous data volume in AAT (see below) an operation without human interaction and a visualization of the progress in measurement is required.
The quality of the digital images may not degrade due to procedural reasons. As this may occur with non-reversible decompression methods, Jaakola and Orava 1994, such principles will not be aplied in AAT.

2.2 Procedural properties

Technical principles of image matching will not be discussed in this paper. Such techniques are explained in great detail in several other publications, e.g. Rosenfeld and Kak 1981, Förstner 1986, Heipke 1990, Agouris and Schenk 1992, Krupnik 1994. Huge data volumes are significant properties for AAT and deserve special attention. Usually digital images are not only needed for the process of aerotriangulation, but also for e.g. the automatic generation of digital terrain models, digital orthoprojection, and digital steroplotting. Thus, these images are scanned in their entirety. The application with the highest demands in accuracy determines the geometric resolution the image is scanned with, and this is aerotriangulation. A geometric resolution of 15 microns is often considered appropriate. This gives the possibility to obtain sub-pixel-accuracy in the order of 1/3rd to 1/5th of the original resolution, and it stays within comparative accuracies as obtained in conventional aerotriangulation measured on analytical stereoplotters. Assuming 256 grey levels, i.e. 8 bit per pixel, and monochrome imagery one obtains storage requirements as presented in table 1.

Geometric resolution	Original image 15 [µm]	Pyramid levels 1 to 6 30 to 960 [µm]	Original + pyramid levels 1 to 6 15 to 960 [µm]	Pyramid levels 2 to 6 60 to 960 [µm]	Original + pyramid levels 2 to 6 15, 60 to 960 [µm]
1 image	0,24	0,08	0,32	0,02	0,26
50 images	12	4	16	1	13
100 images	24	8	32	2	26
500 images	120	40	160	10	130
1000 images	240	80	320	20	260

Table 1: Storage in GB for images with and without image pyramids in aerial image blocks.

Compared to monochrome images, true color images require 3 times as much storage. Large image blocks often consist of 1000 or more images. Thus, special attention is given to these huge data

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volumes in AAT. The active use of image pyramids offers a possibility to eliminate the requirement for integrating compression methods. Table 1 also gives some storage requirements for incomplete image pyramids e.g. by jumping over pyramid level one. It will be shown later that AAT can work with incomplete image pyramids. The storage saving is evident. Using this property one can keep on-line even large aerial image blocks with such geometric resolutions. These aspects are discussed in the following chapters.

3. CONCEPTIONAL ASPECTS

The presentation of the conceptual aspects starts with some considerations regarding the basic approach. Block preparation is done in a different form than that used in conventional aerotriangulation. Of particular interest in the overall procedure are the generation of the topology in higher pyramid levels and measurement in the original images. These two components replace the measurement phase in conventional aerotriangulation. The computation of the bundle block adjustment, the quality control, and the presentation of results are the next and final steps in AAT.
It is important for a sccuessful automatic procedure that there are sufficient checks at appropriate locations in the procedure. This enables AAT to predict the feasibility of the task. AAT is a process which differs in its strategy of measuring from the conventional procedure. Block preparation is fully integrated into the work flow in that it takes place on the same computer. From figure 1 it can be seen that the measurement step of conventional aerotriangulation is replaced in AAT by the two steps *generation of topology* and *measurement*. The bundle block adjustment receives the same type of input data which includes, amongst others, image coordinates of conjugate points. This is the reason why existing program packages can be used in and by AAT without the need for another investment. How a bundle block adjustment program is integrated into AAT is only a question of implementation.
The principle of using image pyramids is fundamental to AAT. As one can see from table 1 the iconic image information of a whole block is accessible permanently. This allows a structural setup of the procedure to generate the topology of the image block and check it for plausibility. After this the actual measurement takes place. Both steps, generation of topology and measurement, make use of automatic measurement procedures. The use of data compression methods can be eliminated by using image pyramids and optimized image access methods. Another important feature is the possibility to divide the image block into sub-blocks. This technique is borrowed from conventional aerotriangulation. Simultaneous processing of the whole block provides the opportunity to obtain final results in a shorter period of time. On the other hand it offers a better overview with accompanying reduction of errors. In AAT sub-blocks primarily help to obtain results faster because several people can work on the same block at the same time.

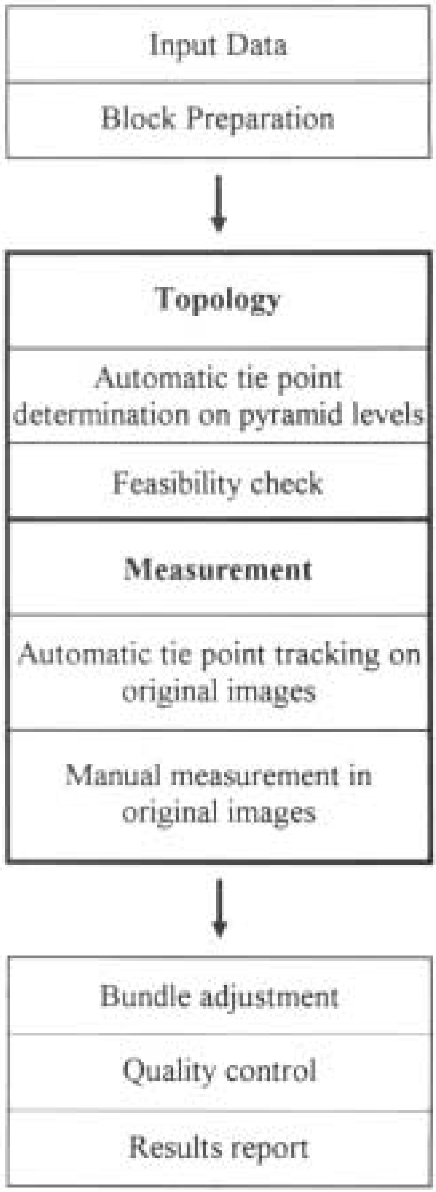

Figure 1: Main components of AAT.

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3.2 Block preparation

Block preparation takes all input data and sets up the image block approximately. The key element of this procedural step is the *table of image centres*. This table contains the most important information, including geometric approximations, of every image in the block. This information is:

- flight number,
- number of each image in flight mission,
- approximations of the coordinates X_0, Y_0, Z_0 of the projection centre of the image,
- approximation of the exterior orientation angle κ.

As usual in aerial photogrammetry, the approximations of the exterior orientation angles ω and ν are set to zero. The azimuth of each image is derived from its κ. Using the approximations of the projection centres and the other available information, it is possible to construct the image block strip by strip. Each strip is a sorted sequence of images of similar azimuths. The result is visualized as wire frame representation of the images composing the block. Until this stage no image data are required. The block will be checked for consistency and completeness. Also, the interactive task of dividing the block into sub-blocks can take place at this stage.
In the next step AAT identifies all images which are part of the block together with their parameters. As such one can consider e.g. the existence of an image pyramid, the existence of the interior orientation, and necessary camera information. Missing parameters are either interactively requested from the user, or AAT determines these data itself, e.g. via automatic image pyramid generation. The methods of automatic interior orientation (Schickler 1995) and image pyramid generation are integral components of AAT. All wire frames can be filled with inconified images. This way one obtains an image visualization of the block which serves for another plausibility check. After the generation of the table of image centres, the generation of topology can take place.

3.3 Generation of topology

In conventional aerotriangulation, point marking and transfer through pugging can be considered as a sort of sum of the generation of topology and measurement in one single step. In AAT the equivalent to pugging is decomposed into two separate but automatically operating steps. The generation of topology consists of the automatic determination of tie points. It is sufficient for this task to be carried out in pyramid levels of lower resolution, i.e. the generation of topology of a *whole block* can be done without having the need to access one single image of original resolution. The geometry of the image block is determined by the generation of topology. The analysis of the block geometry represents the feasibility check of further steps of the automatic procedure, e.g. the feature tracking through several pyramid levels. The goals of feature tracking are the geometric stabilization of the block and the reduction of tie-points down to a minimal yet sufficient number. The results of the generation of topology allow the determination of overlapping areas in images. These areas will then be loaded and used for the final measurement step.

3.3.1 Automatic tie-point determination on lower pyramid levels

This step consists of the relative orientation between images n and n+1 as well as images n and n+2 and the point sorting of conjugate points. The method of automatic relative orientation (ARO) is used. ARO consists of the components *feature extraction*, *feature matching*, *feature tracking*, and *robust parameter estimation* (Tang and Heipke 1994, 1993, Hellwich et. al. 1994). The sorting of conjugate points is oriented along and across the strip direction. Its goal is the detection of 2-fold, 3-fold, and many-fold tie-points. When 4-fold, 5-fold, and 6-fold tie-points are found, it is highly probable that at

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least two strips are tied together, see figure 2. There are different sort criteria available, most of them finding a huge number of tie-points which already define the image block much better than the first approximation in the table of image centres. Now it is the task of error detection to find and eliminate

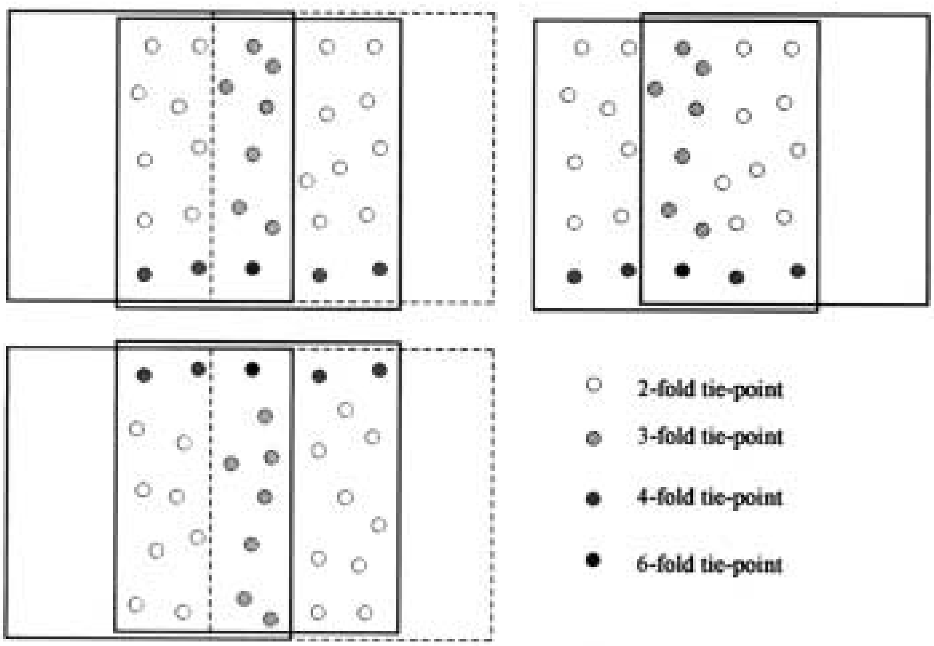

Figure 2: Tie-point locations in multiple overlapping images.

the blunders of automatic tie-point determination.

3.3.2 Feasibility control

During this step of the automatic procedure, all relatively oriented models are transformed into one common coordinate system. In this system the robust error detection takes place. Block geometry and an assessment of the quality of the automatic measurements can be derived from analysis of the results of the error detection. The number of tie-points is decreased due to filtering in the error detection but the image block becomes more stable The remaining tie-points will be processed by the methods of feature tracking down into higher resolution pyramid levels.

3.3.3 Feature tracking through several pyramid levels

In this step of the procedure, the goals are the further stabilization of the tie-points in image space and object space and the determination of more accurate orientation parameters. The reasons for feature tracking in higher pyramid levels are usually one of the following. The feature is

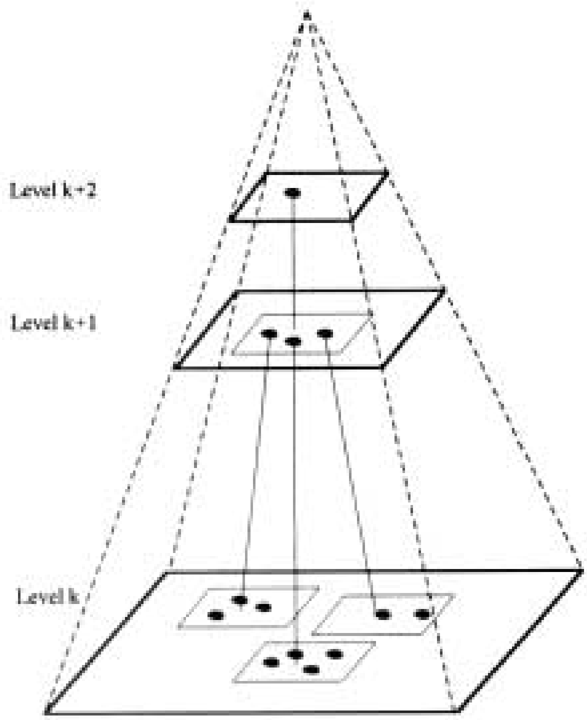

Figure 3: Feature tracking.

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- indicated as a good feature. This is proven if the feature still exists in higher resolution images,
- a representative of several good features. By going into higher resolution images, the feature can be separated clearly from other nearby features,
- a pseudo-feature which disappears on higher pyramid levels. Such peudo-features can come into existence if several grey values in the lower resolution image are accidently gathered into one single grey value.

Applying this strategy, it is possible to set up the generation of topology of an image block almost automatically. The algorithm performs several checks on its own in order to have positive influence on the further automatic progress. Image access to original images is not required. In this stage the image block is checked for consistency. In some instances it is required to start the procedure again.

3.4 Measurement in original images

After the block is accepted to be stable enough, the fine measurement of tie-points, GCPs, and other new object points can start. Due to the huge volume of raster image data, a strategy which fulfills two constraints is to be foreseen:

- Only relevant image windows have to be made available.
- All image windows of multiply overlapping image areas should be kept available during automatic measurement.

AAT can determine all relevant image windows and offers these to the operator to be loaded e.g. from external storage media. The fine measurement is done automatically for tie-points and manually for GCPs and other new object points.

3.4.1 Automatic tie-point measurement in original images

Tie-points are locally determined via feature tracking from lower resolution pyramid levels. The same algorithms as used during the generation of topology are applied. Additionally, a selection of tie-points takes place which reduces the number of points to a sufficient minimum. The criteria used for this reduction are the facts that tie-points should be at or near to the standard locations, their image coordinate residuals after relative orientation fulfill a certain threshhold, and their correlation coefficients are maxima.

3.4.2 Manual measurement in original images

Manual measurement is an integral part of AAT. It is intended to serve primarilly the measurement of GCPs and new object points. Of course, tie-points can also be measured manually. This might be required if either tie-points are to be checked or new tie-points should be introduced into the bundle adjustment. Also, when feature tracking fails, manual tie-point measurement is a necessity.
Regarding the measuring in a digital image and in AAT, there are two basic differences compared to the classical measuring e.g. in analytical stereo plotters. First, the process of measuring can be divided due to its digital media and computer aided measuring procedure into two sequential steps, *localizing* and *identifying*. This process may also be called *digital measurement*. Until now, this process could not be split. In digital images, however, one can approximately define, i.e. localize, a point or the area in which the point resides and leave the algorithm the task of determining its coordinates. Possible measuring principles are e.g. the known image matching methods using least squares matching (LSM) or feature-based matching (FBM). Tie-points are usually determined by applying FBM which finds within a certain area the best possible conjugate points. For GCP-determination and the determination

of new points the LSM principle is often used. Here one point is fixed in one image and then transferred into the other image or images. Basically one can think of this as of a *digital comparator*. It has been shown over time that this way of doing manual measurements in digital images is superior to pure manual measurement which more or less duplicates manual digitizing in the digital image.
The second major difference concerns the multiply-overlapping areas which are an essential part of aerotriangulation. In such areas tie-points have to be measured. The measurement process described above is ideally suited to this task, because it can be extended to virtually *n* overlapping image areas (Heipke 1990, Raad and Scarpace 1995) and measure them simultaneously. This is an advantage of AAT over conventional aerotriangulation. It should also be mentioned that it is possible to perform the manual measurement mode of AAT on its own. One can then think of a *manual digital aerotriangulation*.

3.5 Bundle block adjustment

AAT measures image coordinates. The appropriate block adjustment method is the bundle block adjustment. Regarding the integration of a bundle adjustment package into AAT, one has to distinguish if it is used as a basic component of the measurement part of AAT, e.g. in order to detect blunders, or if it is used for the computation of orientation elements and unknown object coordinates. It is the task of AAT to export the measured image coordinates over a defined interface to the bundle adjustment program and conversely to import the results for quality control purposes.

3.6 Quality control

The results of the bundle adjustment are used to check e.g. blunders. AAT can sort the points geographically and drive the operator to these points in order to visually inspect such areas and to re-measure points. Here the manual measurement capabilities of AAT are used. The obtained results again are to be prepared and processed through the bundle adjustment. This iteration loop is known from conventional aerotriangulation.

3.7 Results processing

AAT delivers a results report which contains adjusted orientation elements of all images, the unknown object coordinates and image coordinates with residuals, and root mean square errors. These are the results of the bundle adjustment which delivers them in list form. For a given stereomodel, AAT should be able to export orientation elements and corresponding GCPs, with their adjusted image coordinates, to an analytical stereoplotter. For the time being it will be, in the majority of cases, an analytical stereoplotter and not a digital one which uses the results of the adjustment in order to set up stereomodels and begin compilation. Special attention has to be given to the required data format for the exchange of this type of photogrammetric data. Further modes of results processing are dependent on the implementation of AAT.

4. IMPLEMENTATION

An AAT-system based on the conceptional aspects described above is the new PHODIS AT from Carl Zeiss. PHODIS AT is part of the family of products within PHODIS, see table 2, and uses the same digital photogrammetric base. The implementation of AAT is founded on the common concepts of PHODIS and application specific requirements of AAT.

PHODIS Product	Photogrammetric Application
PHODIS SC	photogrammetric scanning
PHODIS AT	automatic aerotriangulation
PHODIS ST	digital Stereoplotting
PHODIS TS	automatic DTM-generation
PHODIS OP	digital orthoprojection
PHODIS M	monoplotting

Table 2: PHODIS products and applications in digital photogrammetry.

4.1 General aspects in PHODIS

PHODIS applications collect all relevant data and store them in projects. For the administration of projects, a user interface is available which allows e.g. adding, deleting, copying, and other tasks as well as the generation of a listing, based on which a project backup can be done. In the case of AAT, the project parameters could be e.g. the numbers of strips and images in the block, processed and unprocessed images. The user can exit the application at any time and re-start at the last menu used. For this purpose the system periodically stores the current system parameters.

An important feature in the implementation of PHODIS is the usage of *keywords*. These are either pre-defined, changeable or un-changeable, strings which the user uses as shortcuts in order to avoid long typing. The user can introduce his own keywords. Using keywords one can define the logical structure of data storage locations. The project uses these keywords as logical definitions and substitutes them at run time with physical values. In this way it is possible e.g. to import a project from a backup and adapt the keywords to the situation on the current system, even though this might differ significantly from the original situation of this project. Keywords are available in all PHODIS application programs and offer the user a high degree of flexibility.

PHODIS stores image parameters separate from image raster data in cross-referenced files. Image parameters are e.g. the transformation parameters of the interior and exterior orientations, the reference to the camera, measured image coordinates, and a diversity of status flags, e.g. if an image pyramid is available or not. This strategy allows it to keep bulk data like raster images on external storage devices and still have access to the descriptional parameters of the image. Much information is available in this way to fulfil the data requirements of many application programs. In the preparation phase of AAT, many tasks are done with this information.

If one adopts the principle of separating image parameters from image raster data then it is a small step to also separate image pyramid levels from original image data. In PHODIS it is possible to keep all pyramid levels of an image in one separate file which again is cross-referenced to the files holding the original image and image parameters. Furthermore, it is possible to store only certain levels of the image pyramid, e.g. levels 2, 4, 5, 6. This way only those pyramid levels which are required physically occupy disk storage (see table 1). In other words, unnecessary data are avoided. This is another example of the method of data reduction compared to data compression.

Import and export of raster data in different formats is possible using a data converter available in PHODIS. Data conversion jobs usually run in background or batch. PHODIS handles such processes with its own process handler which sends a message to the user on termination of the job. This frees the user to do other things. Further tools include the administration of cameras and GCPs. An on-line context-sensitive help system supports the user in his interactive work.

4.2 Application specific implementation

Aerotriangulation usually involves a huge volume of data. This requires a structured and interactively guided approach for AAT. PHODIS AT is based on an interactive user interface. The application is not dependent on specific scanner hardware. Nevertheless, PHODIS AT takes digital image data directly from the new PHODIS SC photogrammetric scanner system (Mehlo 1995) which is founded on the same basic principles as all other PHODIS applications.
The table of image centres is an ASCII-file and can be read easily. In this way the user has a simple but effective way of checking and adding information. Based on this, the image block can be visualized via a near-to-reality wire frame model of the block. For each image the user can either display the corresponding overview image or the parameters of that image. The user also can interactively define a sub-block. This information is then used by PHODIS AT to identify all included images and start automatic measurement. The automatic generation of topology is performed in background. The applied principles for measuring are LSM and FBM with a variety of implemented filters. In the manual measurement mode, pugged points can also be transferred into overlapping areas of other images. In such a case, the centre of the pug-hole is assumed to be the point which is to be transferred. The results of the measurement process can be transformed into input data for bundle block adjustment programs, e.g. PAT-B, ALBANY.

5. CONCLUSIONS AND OUTLOOK

As described in this paper, AAT requires a change in work flow compared to conventional aerotriangulation. The main goal of AAT is the *automation of aerotriangulation*. The fundamental differences to conventional aerotriangulation are the automatic and background measurement processes, the intensive user guidance, the ability to measure manually a point in more than two images simultaneously, and to perform plausibility checks at early stages of the overall automatic procedure. By using the technique of image pyramids consequently one can access the whole block at any time. The automatic procedure offers supervised tie-point numeration. This numeration often is a source of errors in conventional aerotriangulation and can take a lot of time to correct. As a disadvantage, one can think of the huge volume of data which requires import and export. However, for this circumstance there are technical solutions under test.
A big potential for AAT is the close cooperation with a rollfilm-capable scanner, e.g. PHODIS SC, and the direct use of data from the flight management system. This heads towards a fully automatic aerotriangulation. Automatic GCP-recognition which implies also the measurement of the identified GCP, still is an open item and the subject of research primarilly. The combination of aerial images with imagery of a different imaging geometry, e.g. SPOT-scenes or three-line-imagery, in AAT is more a question of operational requirement than technical realization. Regarding data archiving, there are now jukebox-systems available which are able to maintain e.g. re-writable magneto-optical CDs with a total capacity of 200 GB. This capacity is permanently accessible to the user. An alternative is to use disk arrays of the same capacity which have the advantage of being truly on-line. The integration of such systems is one of the future extension possibilites to AAT.
The competent use of digital images opens a wide variety of developing complex but automatic measurement tasks. While aerotriangulation is at home in analytical photogrammetry, AAT starts now with its introduction into digital photogrammetry. The author is convinced that AAT will become a standard component of photogrammetric daily work.

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