PRACTICAL EXPERIENCES IN PHOTOGRAMMETRIC PRODUCTION WITH DIGITAL FRAME CAMERA IMAGERY

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ABSTRACT:

Since the first introduction of large format digital frame cameras at the ISPRS2000 conference, these systems have matured and are now widely used in production, by and by replacing film cameras. The advantages of these digital cameras range from an additional near infrared channel, higher bit depth, absence of grain in the image, higher forward overlap without additional cost, to a completely digital workflow. At the same time large format digital frame cameras have been advertised as having the same, well-known geometric characteristics as their predecessors, making their data familiar and easy to work with in an existing production environment. While this of course is true, both data producer and end user or customers are learning the implications for the final product or delivery as well as for the planning, acquisition and production stages.
The paper looks at these aspects during planning, acquisition, and production within the context of generating final products such as orthoimagery and also digital elevation model data. The analysis is developed from the perspective of a private sector production company, and is based on two years of experience in a production environment with tens of thousands of images taken with the UltraCamD and UltraCamX complemented by almost 60 years of experience with film imagery. Project sizes range from 300 to over 10,000 images. These developments are resulting in an evolution of the workflow, leading to tighter system integration and increased efficiencies.

1. INTRODUCTION

Since large format digital frame cameras have first been introduced at the ISPRS 2000 conference in Amsterdam the technology has much matured and is now past its infancy. Many initial technical issues have been resolved. During this transition stage photogrammetric mapping firms have faced several challenges.
First of all, while digital frame cameras are being advertised as having the same well known geometry as analog frame cameras, there are distinct differences. These must not only be understood for production, but must be communicated to the client. The issues range from project design and flight planning to preprocessing the imagery to working with 4-band 16-bit imagery.
In addition to the traditional mapping work there is a high demand for large orthophoto projects, often including automatic terrain extraction (ATE) or LiDAR collection. Thus the number of images being handled by a company per year may have increased tenfold or more. Requirements for accuracy and radiometric quality are high while competition has become fiercer, prompting firms to reduce cost but with the challenge of doing so without compromising quality. This requires adaptation of infrastructure and workflow. If subcontracting is involved, either of the data acquisition or of part of the ground processing, the work at the main production firm is often being shifted from pure data production to quality management. At the same time companies have to deal with a legacy of software packages and systems that may have worked well for 10,000 images per year, but are inefficient for 100,000. Simply increasing capacity by adding software licenses, disk space, network throughput and personnel alone without standardizing operational procedures would result in unacceptable inefficiencies and jeopardize the integrity of a large project.

This analysis is developed from the perspective of a private-sector production company, and is based on two years of experience in a production environment with tens of thousands of images taken with the UltraCamD and UltraCamX complemented by almost 60 years of experience with film imagery. The production environments described and cited are composed of a mix of off-the-shelf systems from different vendors combined with customized workflow procedures. We focus on orthophoto projects flown with the UltraCamD and UltraCamX, including automatic terrain extraction. From analog to digital imagery the annual throughput has increased tenfold. Project sizes range from 500 to 18,000 images. The paper roughly follows the steps of the processing chain, i.e. design and planning, acquisition, processing of the raw data, GPS/IMU processing, aerotriangulation, image balancing, DEM extraction, orthorectification, mosaicking with seamline generation and tiling. Each step includes quality assurance criteria and a quality check step.

2. PLANNING, DESIGN AND ACQUISITION

2.1 Typical sample project and coverage

The design of the UltraCamD and X has been described elsewhere e.g. in (Gruber 2007). One of the main challenges manufacturers of digital frame cameras face is that there is no single chip that can replace a 9 inch by 9 inch film image. Assuming a film resolution of 40 lp/mm or 80 pixels/mm this corresponds to a 2000 dpi or 12.7 micron scan which results in an 18,000 by 18,000 pixel image. For the UltraCamX with a cross track resolution of 14,430 pixels this means that an UltraCamX flight requires approximately 25% more flight lines.

This is an improvement over a few years ago and the gap has become less significant.

UltraCam images are not square, i.e. in flight direction the coverage is smaller than across track. Also the trend is to acquire images at 80 percent or even higher forward overlap. We will address some of the advantages later. That means not only the number of flight lines increases but also the number of images per line. Unlike the number of flight lines this does not result in additional acquisition cost, but rather in additional (possibly only temporary) required storage space.

Throughout the paper we use metric units except where noted. If some values for ground sample distance (GSD) seem odd the reason is that more than 99 percent of our jobs are required in Feet. A typical digital orthoimage job requires orthoimages at 1 ft, 6 inch or 3 inch or 30, 15 and 7.5 cm GSD. A block of 100 square miles flown at 80%/30% overlap with the UltraCamX would then require the following number of images and flight lines (see Table 1):

GSD:	1ft	6in	3in
# flightlines UCD	7	14	27
# flightlines UCX	6	11	22
# flightlines RMK	5	9	17
# images UCD (80%)	259	1022	3915
# images UCX (80%)	180	638	2552
# images RMK (60%) (12.7 micron scan)	45	144	527

Table 1, Number of lines and images for 1 foot, half a foot and quarter foot imagery for a 10 mile by 10 mile block.

2.2 Ground sample distance and accuracy

For “scale-less” GIS data, “representation scale” as well as often the contour interval define the requirements for horizontal and vertical accuracy. For digital frame cameras the achievable horizontal and vertical accuracy can best be expressed as a fraction of the ground sample distance (GSD), see for example (Jacobsen 2005). For targeted points a horizontal accuracy of 0.2 GSD can be achieved. The theoretical vertical accuracy is 0.7 GSD, assuming a parallax accuracy of 0.2 pixels and a base to height ratio of 3.3 for the UltraCamX with 60 percent forward lap. Ultimately, experience will provide proof of the achievable accuracy.

2.3 Preprocessing the virtual image

The “raw” UltraCam data are 13 level-0 files, corresponding to the 13 individual CCDs. In a first preprocessing step immediately following the flight the level-0 data is assembled to level-2 imagery, i.e. the raw data is stitched together to a virtual image (level-1 data only exists as intermediate temporary data). Level-2 data are always provided in a fixed directory structure and contain the full resolution 16-bit (i.e. 12 bit stored as 16 bit) panchromatic and the lower resolution 16-bit, 4-band multispectral image.

Finally, level-3 data are the pansharpened imagery. Unlike in the previous processing steps this step allows for several optional settings, including a 16- to 8-bit conversion, histogram operations, dodging, and output of any band combination. It also allows for a rotation of the image which aligns the image x-axis for instance with the flight direction, which of course changes the location of the principal point. These parameters affecting the geometry, as well as the applied version of the camera calibration are recorded inside the TIFF image header (see Figure 1). It is therefore essential, especially when handling images from different providers to verify these settings in subsequent processing steps and not to lose this information for instance when balancing imagery using third-party software:

```
CAM_ID:              UCX-SX-1-30610302-Rev2
CAPTURE_TIME_UTC:    2008-03-18 18:18:56.421
SOFTWARE:            OPC V3.1.3
IMG_TYPE:            High resolution Color RGB
ROTATION:            0 [degree]
```

Figure 1**,** UltraCam part of TIFF header info

3. AEROTRIANGULATION

Aerotriangulation with digital camera imagery has become highly automated. A well-planned GPS mission and block layout are crucial enabling factors for this automation. Ground control can be reduced to datum definition in the corners and at the center of the block. Processing of larger blocks is typically done in overlapping sub-blocks of about 1000 images that are then being merged for final adjustment. A typical sub-block of 1000 images will have around 10 ground control points. Points at the end of flight lines or cross strips will allow for the correction for GPS drift and shift if necessary. Automatic tie-point matching on a sub-block may run up to 3 hours and can be performed as a batch operation. Blocks then have to be reviewed and ground control can be measured during the workday. Coastal areas or areas bridging large water bodies will have to rely on airborne GPS and IMU data. Other problem areas such as dense tree cover might have to be measured manually with looser restrictions on maximum image residuals. We have tested automatic tie point matching on 16-bit, 8-bit and even 8-bit JPEG-compressed imagery and found no significant differences in tie-point distribution and matching accuracy. However, AT is typically performed using the level-2 panchromatic, a 16 bit TIFF, imagery available the day after acquisition. It is important to note that the tie-point matching benefits from the higher overlap. The first reason is that now each point for example in a block flown at 80%/30% overlap is contained in 5 to 10 images instead of 3 to 6. The second reason is the relatively shorter image size in track direction for digital frame cameras: a typical 2000 dpi scan flown at 60% overlap provides a 3,600 pixel wide strip for finding 3 ray points along track. For the UltraCamX with 60% forward lap this area is reduced to a width of 1,880 pixels.

3.1 Testsite “Pleasanton”

A test site near our office was flown in January 2008 and again in April 2008 (see Figure 2). The January flight was flown with 80%/30% overlap at two altitudes, 233 images in 6 lines at 1100 m AGL resulting in 8cm GSD and 105 images in 5 lines at 1675 m AGL resulting in 12 cm GSD. The April block consisted of 165 images flown at 1675 m AGL and 12 cm GSD in 5 flight lines flown in opposite directions and 2 cross lines. The site contains 15 photo-identifiable ground control points. Vertical accuracy of the points can be estimated to be at 2 cm, horizontal accuracy at 10 cm. Tie point matching was done in Match-AT. Adjustment with and without selfcalibration was performed in Match-AT as well, and similar results were confirmed in BINGO. The following table lists the vertical error (RMS and maximum), based on ground control if all points were used as control, and alternatively based on check points if all or some points were used as check points. The error is listed in cm as well as in units of GSD. The a priori standard deviations were set appropriately.

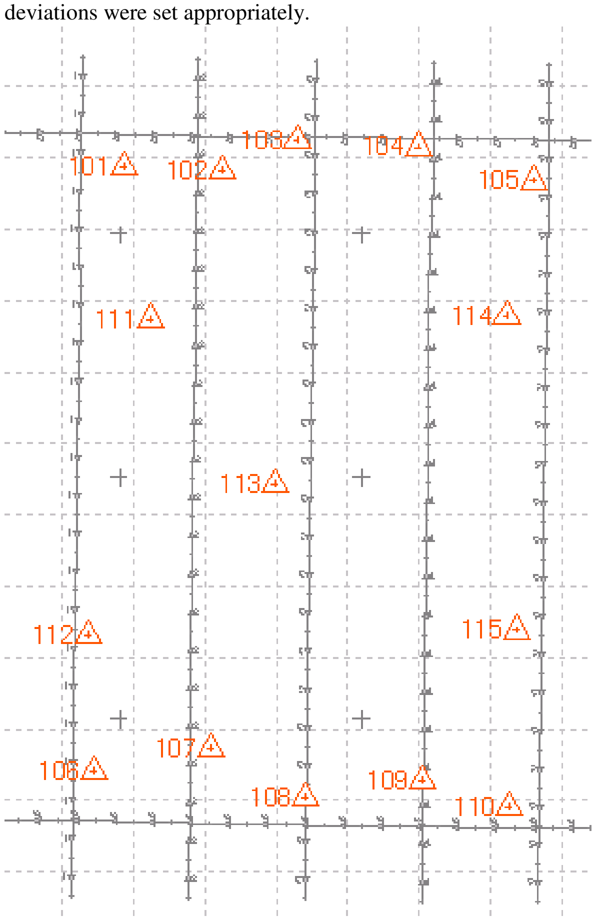

Figure 2, Block layout April 2008

Project	GSD [cm]	Rms_z [cm]	Rms_z [GSD]	Max_z [cm]	Sigma naught
Jan. 15 gcp	8	1.1	0.14	2.2	1.2
Jan. 15 chk	8	4.3	0.5	8.2	1.2
Apr. 15 gcp	12	1.8	0.15	4.4	1.3
Apr. 15 chk	12	11.3	0.9	17.1	1.3

Table 2, Vertical accuracy from 2 test flights

3.2 Example "extreme overlap"

This example was flown with extremely high overlap of 90%/80% over downtown Oakland. It contains 95 images with 15 cm GSD. The block is part of a larger project area. While the complete block contains ground control, this high overlap sub-block does not contain any GCP or check points. A traditional block flown with 60%/30% overlap would contain points that are in up to 6 images. This block contains points that are in up to 50 images. The automatic tie point extraction for this block was run with a pre-release version of Match-AT 5.1 which has been designed to handle such high overlap.

The block was run with self-calibration and the following priori standard deviations: 4 microns for image coordinates, 10 cm for GPS, 0.005, 0.005, and 0.008 deg for IMU.
The block solved with sigma naught of 1.6, RMS for the IMU of 0.002, 0.002, 0.003 degrees, RMS for GPS of 8.5, 6.5, 4.2 cm. The mean standard deviation of adjusted terrain points is 8.4 cm in Z.

3.3 Calibration

For film cameras the standard and required practice in the US has been to calibrate each camera at the USGS facility at least every three years. Initiatives for calibration of digital cameras are described in (Cramer, 2004). Certification aspects are discussed by (Stensaas 2007). With the new multi-spectral capabilities of digital cameras, both geometric and radiometric calibration become important concerns (Cramer, 2004, Honkavaara et al, 2007). This section focuses on the geometric calibration. Traditionally geometric calibration has taken place under clearly-defined laboratory conditions, e.g. at the USGS or manufacturer's facility. (Gruber et al, 2008) describe the calibration of the UltraCamX as a three-step process, consisting of the laboratory calibration, the stitching process and a self-calibration. The lab calibration uses GIP's BINGO software (Kruck 2006) which models the parameters for distortion, shift, scale and skew individually for each of the optical subsystems and CCDs. So far we are not aware of any official statements as to how frequently digital cameras should be recalibrated. Microsoft/Vexcel's OPC software generates a virtual level 2 panchromatic image by stitching together the level 0 data of the 9 individual CCDs. This process can only be monitored by the user. The self-calibration finally depends of course on the AT software used and the results then have to be incorporated in subsequent processing steps. Over the last two years we have used several UltraCamD and UltraCamX cameras. Figure 3 shows a sample plot of UltraCamX distortions, plotted in Match-AT which shows a clear pattern of the individual optics subsystems. Although the maximum residual at the extreme edge is almost 4 microns, the residuals inside are much smaller with a maximum of 1 or 2 microns (Figure 4). These distortions can of course be applied to a grid. The difficult part in production environments that often use systems from different vendors is how to transfer this data to the compilation or orthophoto software. (Becker, 2007) and others therefore suggest that camera manufacturers include this in their preprocessing to the virtual images (instead of e.g. having the user perform a second resampling). Vexcel suggests that these remaining distortions can be modelled as radial distortions which can be handled in most systems. In our experience a self-calibration in the bundle adjustment can improve the sigma_naught by 5 to 10% and the vertical accuracy by a factor of two.
With the advent of airborne GPS a calibration of the entire system of camera and GPS gained importance. Now, with the complex interaction between camera sensors, GPS, IMU, flight management systems and gyro-stabilized mount, an overall system calibration in addition to the laboratory camera calibration becomes essential. Time is the key to integrate data from the different systems, including the synoptic image recording of the UltraCam itself. In addition to flying a boresight calibration over a well-controlled test field at regular intervals, a boresight can be computed from every mission. Any possible timing errors, e.g. between camera and GPS, have to be observed carefully. In a busy production environment regular calibration results and any development has to be documented carefully to confirm stability of the system between calibrations.

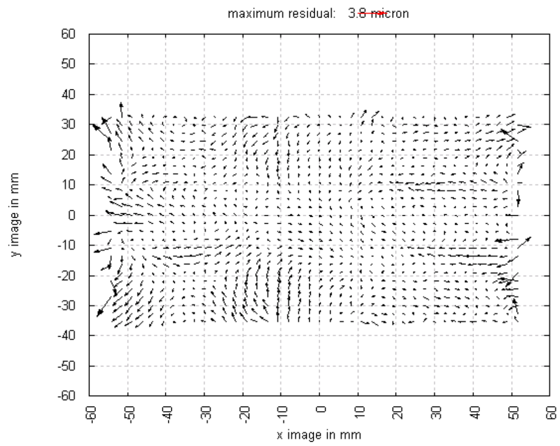

Figure 3, Distortion grid, (exaggerated vectors)

-3.84	-0.78	-0.49	0.51	4.31
0.74	-1.22	-2.22	-0.94	2.31
1.57	2.16	1.06	-0.54	-0.92
-0.26	-1.80	-2.29	-1.88	-0.90
1.01	1.25	0.19	-1.04	-1.16
0.50	0.19	0.04	0.15	0.17
-1.43	0.01	-0.27	-0.87	-0.04
-0.29	0.72	1.56	1.44	0.44
-2.80	-1.21	-1.44	0.83	3.96
-0.91	1.36	0.81	1.92	0.36

Figure 4, Distortion values in micron at 25 grid points

3.4 Airborne GPS and IMU

Ground control design and software for automatic tie point matching rely on airborne GPS and INS data. Data is collected with the Applanix AV-510. The flight is planned with at least one dedicated basestation or a CORS basestation within 30 km plus one backup basestation. At least two basestations are being used, both to avoid datum errors and to increase accuracy. Different postprocessing modes are available:

- GPS-aided inertial navigation with the described setup is currently in use.
- Applanix In-Fusion technology promises a more accurate and robust solution through tighter integration of GPS and INS observations. This methodology is currently being implemented.
- Applanix SmartBase solution allows for longer baselines using the concept of a virtual reference station (see Figure 5) and is currently under testing for production.
- Precise Point Positioning uses the precise ephemerides and allows for processing without any basestation. It achieves almost the accuracy of aided inertial navigation, but has the disadvantage that there is no datum check.

GPS data must be processed and evaluated immediately following the flight to check if any reflights are necessary, e.g. due to too high crab angles etc.

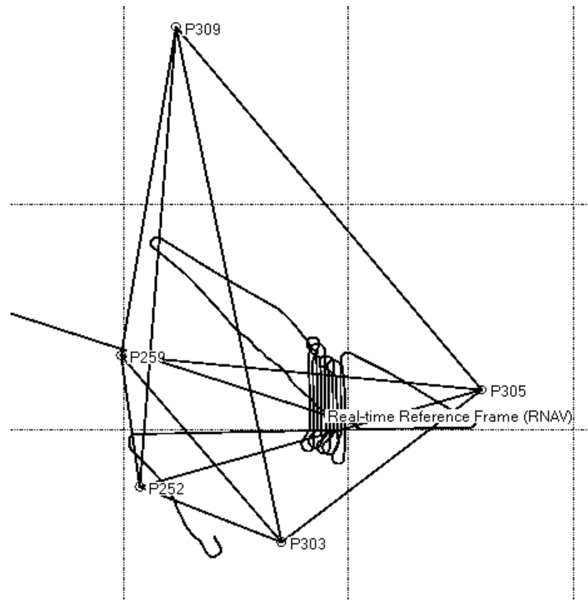

Figure 5, Virtual basestation

4. DEM

Both LiDAR and automatic terrain extraction (ATE) by image-matching techniques are being used to generate elevation data for large areas, subsequently to be applied as the foundation to support orthorectification. Generating elevation data through image-matching has the advantage that no costly LiDAR acquisition is needed and the elevation data can be generated from the same imagery. A disadvantage of ATE may be that the computation times are high, i.e. processes for several thousand images may run over weeks on a single workstation, and therefore such steps are well suited to a distributed processing environment. Both techniques require inspection and possibly manual editing. In this chapter we don't want to compare the two but rather look at automatic terrain extraction by itself. Automatic terrain extraction has been in use for a while (Braun 2007) on typical 60%/30% aerial frame imagery and for larger scales it has always required a significant amount of manual postprocessing in the form of inspection and editing. Problem areas have typically been in areas of low texture or regions such as agricultural fields that exhibit regular patterns that might produce spikes in the elevation data, although improvements in robustness have been achieved (Braun 2007) and (Zhang et al 2007). With digital imagery a much higher forward overlap, e.g. 80%, is possible at no extra acquisition cost. Most commercial ATE packages have been enhanced over the last years to be able to perform multi-ray matching. For example, with 80% forward overlap each point on the ground is covered by at least 5 instead of only 2 images. This can greatly improve the robustness and possibly the accuracy of the elevation (Thurgood et at 2004). Over the last two years we processed several thousand square miles of elevation data from imagery flown with the UltraCamD with 80%/30% overlap at an altitude of 7300 m, generating elevation data with a 6 m (or 20 foot or 10 GSD) spacing approximately. Without going into specific details here, especially with hardware changing so quickly, it is important to note that a typical county-sized area can easily take 2 weeks of CPU time.

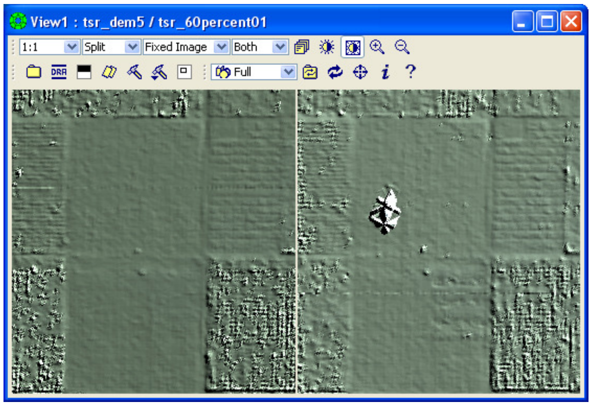

Figure 6, digital surface model derived from 80% (left) and 60% (right) overlap with the UltraCamX

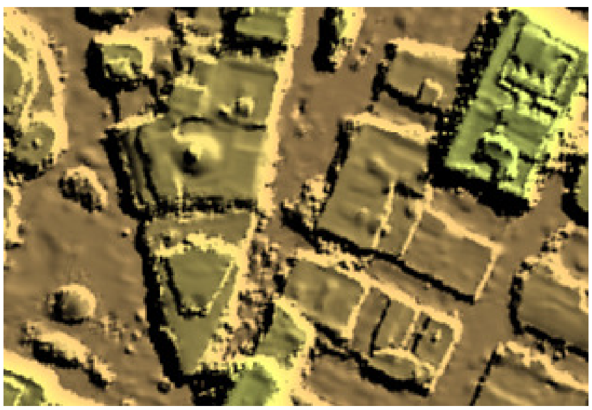

Figure 7, Surface extraction from a 90%/80% flight over Oakland, California

The following example stems from a flight with the UCX over an agricultural area over the Central Valley in California. The imagery was flown with 80%/30% overlap and 0.5 ft GSD. A digital surface model was generated both from 80% and from 60% overlap. 3300 tie points from the automatic AT were used as checkpoints on a sample of 3 flight lines. Using a large number of tie points as check points in addition to the use of a few surveyed check points on well defined surfaces allows for a practical and automated check in a production workflow. The results contained a few large outliers, mainly at the edges of the DTM. After one outlier removal (removing points with residuals larger than 3 sigma) the RMSE_z for the 80% data was 1.1 ft or an improvement of 10% over the standard deviation of the 60% data. The most significant difference, however, was the DSM from the 60% data required significantly more manual edit than the DSM from 80 percent data, which requires no edit at all in open areas (Figure 6).

These examples (see also Figure 7) have been generated with ATE SocetSet by BAE. In a few problematic cases (areas with swamps and wetlands for instance) much better results could be achieved with NGATE (Zhang et al 2007), although at the cost of a considerably higher computation time.

5. ORTHOIMAGES

Orthoimagery has long become the standard base layer for GIS. True orthoimagery although first introduced by Helava in SocetSet about 20 years ago is still in low demand. This is mostly due to the high cost of collecting building data. But our impression is that the user actually misses the impression of height of buildings when all remaining building lean has been removed, which of course contradicts the concept of a map. For road bridges on the other hand a removal of any distortion due to DEM effects is expected. This problem has already become much less significant when flying with 80 percent forward lap. Only narrow “orthoareas” need to be rectified. Due to the high overlap these areas are much more nadir than used to be the case for film imagery flown at 60 percent forward lap. In addition to this any low altitude flight would usually include additional spot shots over complex elevated structure (see Figure 8, San Francisco international airport)

Figure 8, Even if no correction of building lean in the orthoimage is required, elevated freeway structures must be dealt with

A far more interesting question for the future is if and when the 2.5-D representation of the terrain will be replaced by a true 3-D representation and how orthophotos may be integrated with 3-D reconstruction, see also (Snavely et al 2006).

6. PROJECT, WORKFLOW AND INFRASTRUCTURE

The previous section touched some aspects of the workflow, mostly focusing at the geometric aspect more than at the radiometric. At first sight the workflow is not much different from the one using film. Most importantly a re-examination of quality assurance (QA) procedures and quality check (QC) steps has to take place (Figure 9). QA standards and QC procedures must be documented. Raw data (image and GPS) must be archived directly after the flight. Subsequently any setup data including the software version used must be archived, so that it is possible to recreate the processing steps at any time later. Radiometric properties are quality checked based on the level0 and level2 imagery. Necessity of reflights is checked right after the flight based on the GPS. The AT will reveal possible calibration problems.

The delivery of 8 or 16 bit data and of 3 band or 4 band data as well as the clients intended use of the data and expectation regarding balancing have to be discussed. If, as it is generally the case, 8 bit data will be delivered, the conversion from 16 bit to 8 bit and possibly from 4 bands to 3 bands can take place at several points in the workflow.

With the transition to digital project the data amount and throughput has increased manifold for most companies. A clear definition of the workflow is therefore more important than ever. Many companies are dealing with an ad hoc growth (Greening 2001), using a patchwork of systems. Interfacing is still a problem, although standardization has become better and systems providers implement interfaces to their competitor's systems.

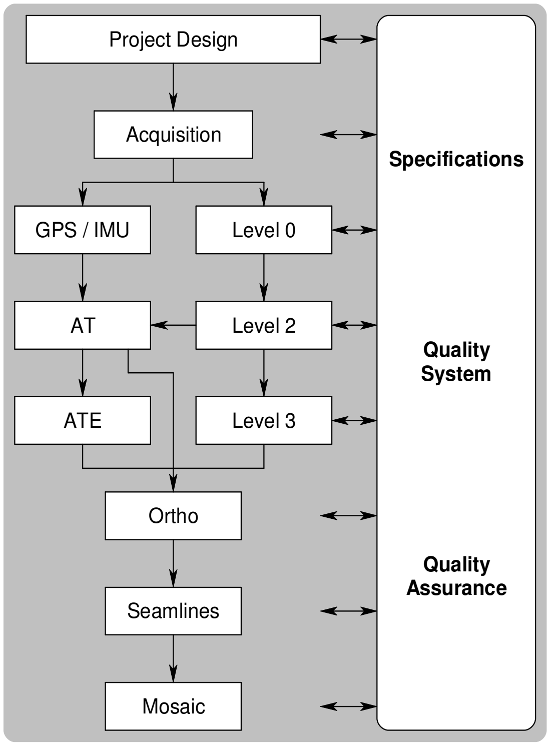

Figure 9, QA/QC steps for the digital workflow must be adapted

Efforts to deploy photogrammetry-specific workflow management systems started probably with Terrashare (Greening 2001) and continue, e.g. with GeoCue (Flood et al 2008), although many organizations continue to set up their own systems. A trend is to streamline processing as in the Leica ortho accelerator and to use distributed processing (Braun 2007).

7. CONCLUSIONS

Digital frame camera imagery allows for a completely digital workflow and has clear advantages over film in terms of geometric accuracy and stability as well as radiometric and spectral resolution. Within individual stages of the production process, such advantages have translated into improvements in operational efficiency that can be measured and realized. However, the overall workflow, although identical at first sight, requires significant rethinking. What is critical is a completely new view of the data flow and the processing chain from planning and design, flight operations, through the various in-house production steps, and the implications for resource planning to support this flow. In addition, there are many other related areas which impact the practical application of the digital camera. Possibilities and options of new multispectral imagery, and the broader set of possible products have to be communicated to the client. The project manager has to understand the implications for project design. New QA/QC procedures have to be documented. As the application of digital frame cameras becomes ever more mature, these issues will be addressed fully.

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