PHOTOGRAMMETRIC SOFTWARE FOR THE LH SYSTEMS ADS40 AIRBORNE DIGITAL SENSOR

Udo TEMPELMANN[1], Anko BÖRNER[2], Bruce CHAPLIN[3], Ludger HINSKEN[4], Borys MYKHALEVYCH[2], Scott MILLER[3], Utz RECKE[1], Ralf REULKE[2], Robert UEBBING[3]
[1]LH Systems GmbH, Switzerland
recke@lh-systems.com, tempelmann@lh-systems.com
[2]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany
Institute of Space Sensor Technology and Planetary Exploration
anko.boerner@dlr.de, borys.mykhalevych@dlr.de, ralf.reulke@dlr.de
[3]LH Systems, LLC, USA
chaplin@lh-systems.com, miller@lh-systems.com, uebbing@lh-systems.com
[4]Author of ORIMA, Germany
ludger.hinsken@surf24.de

Working Group IC-8

KEY WORDS: Camera, CCD, Sensors, Photogrammetry, Mathematical Models, Data Processing, Software.

ABSTRACT

Airborne linear array sensors present new challenges for photogrammetric software. The push-broom nature of these sensor systems has the potential for very high quality images, but these are heavily influenced by the dynamics of the aircraft during acquisition. Fortunately, highly precise position and attitude measurements have become possible, using today's inertial measuring units (IMUs). This allows image restoration to the sub-pixel level. The sensor discussed in detail here is a "three-line camera" with additional multispectral lines. The three lines are one looking forward, one in the nadir position and one looking backward with respect to the flight path.

Extensive software processes are necessary to produce traditional photogrammetric products from a push-broom airborne sensor. The first steps of the ground processing flow are off-loading imagery and supporting data from the mass memory system of the sensor, post-processing of GPS/IMU data and image rectification into stereo-viewable and matchable form. After this processing, the images can be used similarly to classical aerial photography. This includes semi-automated triangulation with and without ground control, DTM production from multiple stereo views, vector extraction in mono and stereo, and orthophoto and mosaic production. The paper analyses the differences to classical photogrammetric processing for all processing steps and closes with a discussion of the advantages and disadvantages of this new type of photogrammetric imagery.

1 INTRODUCTION

Airborne digital sensors are making an ever larger contribution to the extraction of information by photogrammetry and remote sensing. The promise of these digital sensors comprises many potential benefits over traditional film acquisition, including improved radiometry, elimination of film processing and scanning, near-real-time data exploitation and improved multispectral image acquisition. For many applications, digital sensors are providing improvements in cost or performance over traditional film cameras. For some traditional uses, however, film camera systems will remain more efficient for some years.

This paper presents the ground processing flow designed for the LH Systems ADS40 airborne digital sensor, which contains several linear array sensors on a single focal plane with a single compound lens. The push-broom characteristic of this geometric configuration presents many new challenges for photogrammetric software. The linear array sensors provide excellent radiometric resolution, which the ADS40 combines with a highly stable inner geometry, but the raw imagery is heavily influenced by the dynamics of the aircraft during image acquisition. This results in high quality imagery that must be "reassembled" to provide images interpretable by humans. Fortunately, today's excellent inertial measurement units (IMUs) allow precise measurement of the dynamics of the imaging platform to the sub-pixel level.

This paper starts with a short description of the camera configuration and the typical image acquisition characteristics. This is followed by the ground processing flow, including archiving, rectification, triangulation, and product generation.

2 OVERVIEW OF THE ADS40 CONFIGURATION AND IMAGE ACQUISITION

The ADS40 has seven parallel sensor lines - three panchromatic lines (forward, nadir, backward), three colour lines (red, green blue) and one near infrared - in the focal plane of a single lens system. The three panchromatic sensor lines produce the forward, nadir, and backward views along the strip. This yields the stereo angles shown in table 1. Each panchromatic line consists of two linear arrays, each with 12000 pixels, but staggered by 0.5 pixels as shown in figure 1. The colour lines (red, green, blue), each 12000 pixels long, are optically superimposed during the flight. This is accomplished with dichroitic mirrors, which divide a single light ray into its three colour components without significant energy loss, followed by narrow-band filtering, to increase the channel separation for remote sensing applications of the camera. The great advantage of this approach is that the colour image is band registered without significant post-processing and thus results instantly in an attractive colour picture. Without the dichroitic mirror arrangement, a high-quality composite from three lines with different nadir-offsets would only become available after rectification using a surface model. The near infrared sensor lines are 12000 pixels long and slightly offset from the RGB triplet. The precise position of each pixel is known after the calibration process. This results in a look up table that is used to correct for displacements mathematically.

Focal length	62.5 mm
Pixel size (pitch)	6.5 µm
Panchromatic line	2 ∗ 12000 pixels
RGB and near IR line	12000 pixels
Forward to nadir stereo angle	26°
Forward to backward stereo angle	42°
Nadir to backward stereo angle	16°
Red band	608-662 nm
Green band	533-587 nm
Blue band	428-492 nm
Near infrared band	703-757 nm
Near infrared option	833-887 nm

Table 1. ADS40 characteristics

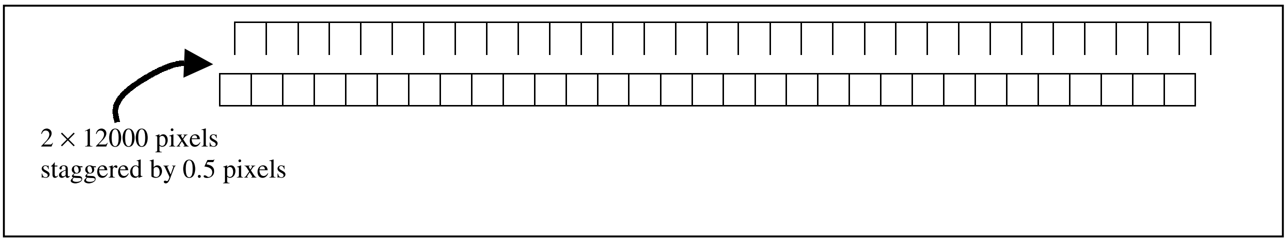

Figure 1. Design of panchromatic line

As the aircraft progresses along a strip, the imagery is acquired by high frequency sampling of the sensor lines. This is referred to as “push-broom” acquisition. The frequency of read out varies with flying speed and height but is typically in the range of 200 to 800 Hz. The raw images contain distortions due to aircraft roll, pitch, yaw, vibrations and XYZ displacements while the imagery is being acquired. Figure 4 shows a panchromatic image with distortions due to aircraft motion during image acquisition.

During the flight, imagery, GPS position data, IMU data and other house-keeping data are written to a removable disk pack called the mass memory system (MMS), which contains six high speed SCSI disks and is hermetically sealed and mounted in shock absorbers to withstand the varying pressure and vibrations. During the flight, imagery is acquired from all sensor lines simultaneously. The camera computer saves the data to the MMS in a special format where blocks of lines from the different sensors are interlaced through the simultaneous read out of multiple lines. The data throughput to the MMS and the MMS capacity are improved by image compression implemented in hardware. This consists of a block-wise image normalisation to 8 bits, followed by lossless or baseline JPEG compression with adaptive Q-factor regulation.

3 OVERVIEW OF CAMERA TO GROUND PROCESSING

The ground processing system reads from the MMS and archives the data before starting further processing (figure 2). After archiving, the GPS/IMU data is processed with the GPS base station data. This results in position and orientation files which are use to create Level 1 rectified images, which are human viewable, ready for processing in many classical remote sensing systems and used to perform triangulation, compilation, DTM production, etc. Further image analysis products and level 2 rectified orthophotos can also be created. Colour, black and white, and multispectral orthophotos can be generated.

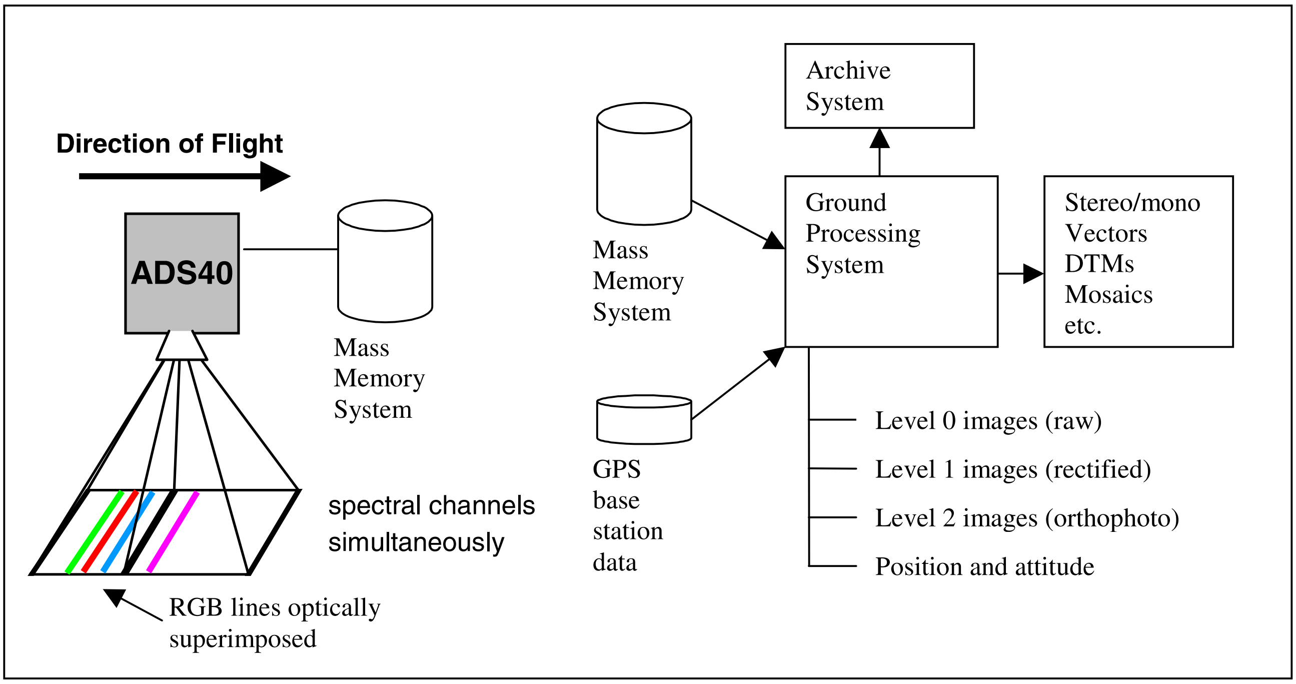

Figure 2. Direct digital workflow

The major functions performed by the ground processing system are (figure 3):

(i) Off-loading imagery and supporting data from the mass memory system of the sensor and conversion into a standard form (Level 0 data product)
(ii) GPS/IMU post-processing for harmonisation of the instantaneous position and attitude of the sensor
(iii) Image rectification into stereo-viewable and matchable form (Level 1 data product)
(iv) Semi-automated triangulation with and without ground control
(v) DTM production from multiple stereo views
(vi) Orthophoto and mosaic production (Level 2 image products)
(vii) Vector extraction in mono and stereo from Level 1 images
(viii) Data handling, product formatting, archiving.

4 UNLOADING THE AIRCRAFT

After the aircraft lands, the disk pack is removed from the camera control system and taken to the ground processing system, where it is connected to the SCSI interface of the computer. Here the data are offloaded on to the ground disk storage system. During the offloading, the data are split into the single images, orientation data and housekeeping information files. The resulting data structure is called the Level 0 data product. The ground processing computer is an off-the-shelf Windows NT® system with a standard SCSI interface. To reduce the time required to offload the MMS, the imagery is normally maintained in the compressed format of the camera but reorganised by image sensor lines (bands). Optionally the images can be converted directly into standard 12- (16-) or 8-bit data formats.

In order to store the large continuous image strips on standard file systems, the Level 0 images are split into near-square non-overlapping blocks, but the ground processing system still handles the imagery on a per-strip basis, hiding the low-level blocking from the user. The blocking is also essential if the imagery is going to be handled in environments other than the ADS40 ground processing system. Many software products are limited in the image sizes they can handle.

5 ARCHIVING THE DATA

Since the system is digital and the imagery does not exist on film, it is critical that the imagery is archived on reliable media. After the imagery has been transferred from the MMS to the ground processing system disks, it can be archived on to suitable media such as DLT (Digital Linear Tape). A typical flight can produce around 200 GB of compressed data. Offloading the MMS and archiving the data takes several hours using today's typical computer peripherals. As an example, at 40 GB per tape, several tapes will be used to archive a typical mission of 200 GB of compressed data. By using a DLT juke box system, the imagery and supporting data can be completely archived in an unattended operation over several hours.

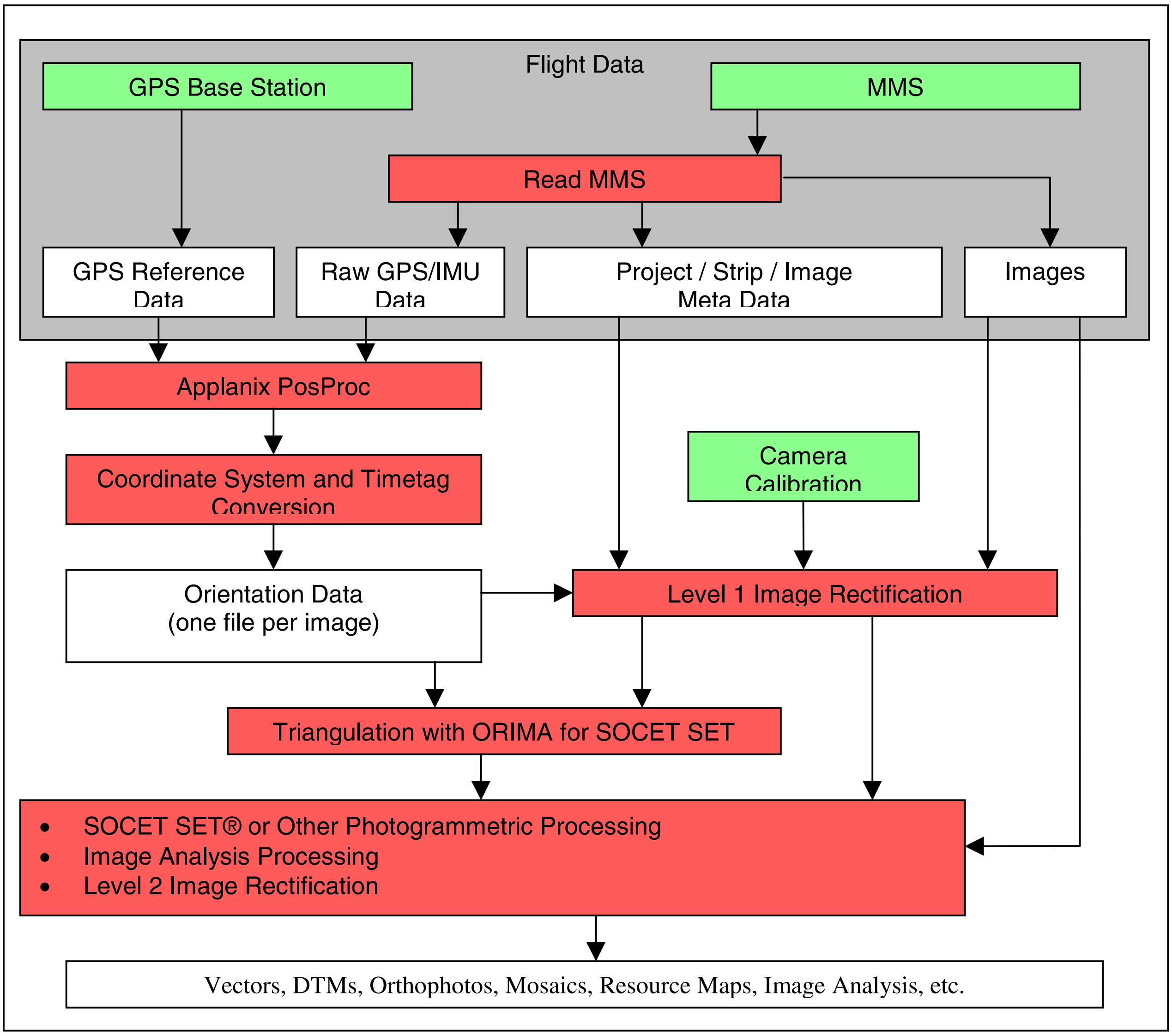

Figure 3. Ground processing flow

6 GPS/IMU POST-PROCESSING

GPS and IMU data are collected during the image acquisition and written to the MMS. These two data streams must be post-processed along with optional GPS base station data, to produce a precise position and attitude stream for every line of imagery. Since different lines may be using different sampling frequencies, the data are processed into separate files for all sensor lines. Thus, at the end of this processing step, there is one data file for each sensor line, containing the position and attitude for each line of the image.

The GPS data is recorded referenced to the World Geodetic System of 1984 (WGS 84). This gives the position of the GPS antenna. The IMU system records instantaneous changes in position and attitude of the ADS40. The IMU is rigidly attached to the focal plane/lens system unit. The high frequency readout of the IMU is used to verify the GPS data and to provide instantaneous positioning of each line of imagery between GPS recordings. Since the sampling frequency of the imagery may typically be as high as 800 lines per second, while the GPS frequency may be 2 samples per second, the IMU must be used to determine the precise position between GPS samples. Likewise, the IMU provides high frequency readout of sensor attitude. The IMU system generates *relative* position and attitude information. Thus it provides very precise position and attitude only over short periods of time. As time increases, the position and attitude accuracy drifts away from the true position and attitude. This attitude data must be corrected and transformed to real world coordinates by using the GPS data. Thus, the GPS data is also used to correct the bias and drift of the IMU system. The IMU records attitude referenced to the “local vertical” (plumb line direction). Corrections can be applied for deflection of the vertical direction, the alignment of the IMU coordinate system with respect to the focal plane coordinate system and the GPS antenna offset. Moreover, the data can be corrected further during a triangulation process described below.

To produce the initial position and attitude files for each image, the data must be processed into a local rectangular reference frame. Defined to be Cartesian and centred in the project area, this local reference frame is used to support the attitude data and the triangulation.

The GPS/IMU processing is an important step towards high quality imagery and accurate measurements derived from it. The timing of IMU recording, GPS recording and sensor line recording must be done using a synchronised clock. This allows the precise registration of each data-recording event. To perform data collection from imagery without triangulation, care must be taken to handle each error source.

7 IMAGE RECTIFICATION

After the GPS/IMU data has been processed, the position and attitude files and a simplified interior orientation of the camera are used to rectify the images. In the standard processing flow, the images are projected to a ground plane at a user-specified elevation. This allows the correction of the aircraft motion in figure 4 and results in the attractive, viewable image in figure 5. These rectified images are referred to as Level 1 rectified images. They can be put into standard formats and processed more easily by standard software packages, and are easily viewable. Long strips of imagery are created from the continuous imaging that occurs during a flight strip. The rectified image is broken up into large blocks of a user-specified size, which however are still treated as continuous strips by the ground processing system. Each block can be written in standard formats such as 8-bit TIFF, 16-bit TIFF and tiled TIFF. The standard Level 1 image is an approximately geopositioned image. It is ready for processing in standard image processing and remote sensing packages. Furthermore, it is ready for human stereo viewing and point measurement using image matching techniques and other automated processes.

Figure 4. Level 0 (unrectified) image

Figure 5. Level 1 (rectified) image

During the rectification process, a look up table is also created which provides a direct means for transforming from the once-rectified image back to the Level 0 (raw) image. This allows the mathematical model from ground to image and image to ground to work efficiently and exactly. This information is necessary to recover the instantaneous position and attitude associated with any pixel in the Level 1 image. Once the imagery has been rectified to Level 0, triangulation can take place if required.

To exploit the resolution of the ADS40 to the full during interactive feature extraction, a second form of rectification is available, which uses an approximate DTM to correct the images from the disturbed push-broom-view to an idealised one. This “Precision Level 1” imagery is generated using both lines of the staggered pairs and also the full interior orientation of the camera, as determined during geometrical calibration. This results in high-resolution stereo-viewable imagery, free of the small residual errors that can show up in the standard Level 1.

8 AUTOMATED TRIANGULATION

The ADS40 does not use the highest quality, expensive gyro systems to achieve highly precise attitude data over long flight lines. Instead, aerial triangulation is used to combine the high local, i.e. short-term, accuracy of the IMU with the high global accuracy of GPS. In combination with a minimum number of ground control points, aerial triangulation delivers best fitting results on the ground. The extra information added to the system by tie point measurement leads to very reliable orientation results where photogrammetric measurements serve to control IMU/GPS measurements and *vice versa*.

The triangulation process involves automatic measurement of tie points and interactive measurement of control points. All operations are performed using the graphical working environment of ORIMA (Hinsken *et al*., 1999). For automatic tie point measurement the APM software module from SOCET SET®, adapted for the ADS40, is called directly. Highest quality orientation results are obtained by a combined bundle adjustment. The Combined Adjustment Program CAP-A, which is part of ORIMA, has been extended to handle all types of observations required for ADS40. The observations are image coordinates, and position and attitude values from GPS and IMU computed by IMU/GPS post-processing software. The post-processing includes the transformation of the raw data into the reference frame used for the aerial triangulation. The resultant values of this transformation are usually fairly close to the exterior orientation elements of photogrammetry.

Aerial triangulation for the ADS40 is also required to compensate systematic effects, primarily the misalignment between IMU and camera axes and the datum difference between IMU/GPS and the ground control coordinate system. The observation equation used to compensate datum differences is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{GPS} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \lambda \cdot \mathbf{R} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{PC} \tag{1}$$

The left-hand side shows the coordinates as the result of the IMU/GPS post-processing, which also handles the offset between antenna and projection centre. The right-hand side shows the coordinates of the projection centre as computed in the bundle adjustment by photogrammetric observations. In between we have the seven parameter rigid body transformation. These parameters are estimated during the bundle adjustment.

Since the camera and IMU axes are designed to be parallel, the following observation equation is used to calculate the misalignment between IMU and camera axes:

$$\begin{bmatrix} \omega \\ \varphi \\ \kappa \end{bmatrix}_{IMU} = \begin{bmatrix} \omega \\ \varphi \\ \kappa \end{bmatrix}_{PC} + \begin{bmatrix} \omega_0 \\ \varphi_0 \\ \kappa_0 \end{bmatrix} \tag{2}$$

The left-hand side shows the angles obtained from the IMU/GPS post-processing. The right-hand side shows the angles as computed in bundle adjustment by photogrammetric observations. The third vector, with subscript 0, indicates the misalignment between the two systems. This is estimated within the bundle adjustment. The angles describe the rotation from the ground system to the camera system.

To handle the multi-line sensor geometry the generalised collinearity equations described by Müller (1991) are used. This technique determines the orientation for sensor lines at a certain interval. These positions are called orientation fixes. The orientations of the sensor lines between two orientation fixes are determined by interpolation using the IMU/GPS values. The collinearity equations, which describe the relation between a point in the ground system and in one image, are generalised such that every point in the ground system falls between two orientation fixes:

$$x_i = F(X_i, Y_i, Z_i, X_k, Y_k, Z_k, \omega_k, \varphi_k, \kappa_k, X_{k+1}, Y_{k+1}, Z_{k+1}, \omega_{k+1}, \varphi_{k+1}, \kappa_{k+1}) \quad (3a)$$

$$y_i = G(X_i, Y_i, Z_i, X_k, Y_k, Z_k, \omega_k, \varphi_k, \kappa_k, X_{k+1}, Y_{k+1}, Z_{k+1}, \omega_{k+1}, \varphi_{k+1}, \kappa_{k+1}) \quad (3b)$$

These are the generalised collinearity equations for image coordinates x, y of point i. They are functions of the orientation fixes k and k+1. The distance between two neighbouring orientation fixes is defined in such a way that systematic errors caused by gyro drifts can be compensated.

The combination of different types of observations within the bundle adjustment requires a proper weight relationship among the different groups. The correct weight relationship is obtained by variance component estimation.

ORIMA allows for a combined triangulation of images from conventional aerial cameras and from the ADS40.

9 STEREO VISUALIZATION AND VECTOR EXTRACTION

The ADS40 acquires continuous long strips of stereo coverage. Since these images may be too long for typical disk file sizes, the images are partitioned into roughly square blocks. A new image type has been added to SOCET SET to allow continuous roaming over these very long partitioned images. In addition, the stereo models consist of three options for stereo viewing: forward/nadir, forward/backward, and nadir/backward. The user can perform data extraction and stereo viewing using any of the three combinations. This is a very useful capability and allows more optimal viewing, particularly for objects with considerable relief such as buildings, trees and mountains. This also provides redundancy for triangulation, DTM production and interactive measurement. All the typical photogrammetric data extraction operations can be performed and SOCET SET modules, such as PRO600 for MicroStation® GeoGraphics®, work in the standard fashion.

10 AUTOMATIC PRODUCTION OF DIGITAL TERRAIN MODELS

Using standard Level 1 images, the SOCET SET Automatic Terrain Extraction (ATE) module is used to create grid or TIN DTMs. Here again, the advantage of ATE is shown with respect to the multiple stereo views. Since ATE is truly a multiple image algorithm (Zhang and Miller, 1997), it will take advantage of the forward/nadir, forward/backward and nadir/backward stereo views to produce better DTMs. These stereo angles, combined with the better signal-to-noise ratios typical in digital imagery when compared to scanned film, will yield improved DTM quality and reduce human editing time. The amount of occluded surface is also reduced owing to the three viewing angles.

11 CREATION OF ORTHO-MOSAICS

Ortho-corrected image products can be generated from Level 0 or Level 1 image products. To make an orthophoto from the Level 1 rectified product is straightforward given the Level 1 mathematical model. SOCET SET can be used to create orthophotos and mosaics in the normal way when using the Level 1 rectified imagery.

Orthophotos can also be generated directly from the Level 0 image. In this case, to take advantage of the staggered arrays (as shown in figure 1), the software resamples the imagery from the higher resolution staggered sensors. A direct high-resolution true-colour composite is possible by combining the RGB lines with the staggered panchromatic nadir line.

12 DISCUSSION

We have tried to summarise some of the photogrammetric processing to be used with the LH Systems ADS40. Airborne digital sensors are starting to make a large impact on the way photogrammetry and remote sensing are performed. Linear array “push-broom” sensors offer new opportunities for GIS data production. Some of the positive aspects include:

- One lens, but the ability to collect multispectral data in one flight pass
- Higher signal-to-noise ratio than is possible with film cameras or frame CCD sensors
- No need to process film
- No need to scan film
- Multiple stereo configurations

- Ease of automatic (batch) processing on standard workstation platforms
- No triangulation required for medium accuracy products.

There are also some hurdles to jump compared to traditional film processing, including:
- Linear array sensors do not yet have the resolving power of traditional aerial film cameras.
- It is not as easy to create the long-term archive since the imagery is not on film.
- It is not yet possible to fly easily at low altitudes in fixed wing aircraft owing to data readout time.

Many of the processing steps appear quite traditional. Existing products such as SOCET SET and ORIMA for SOCET SET are used to perform seemingly standard photogrammetric production. Behind the scenes, the mathematical models and GPS/IMU processing are more complex than traditional frame data processing. The extraction of vector data and the editing of DTMs will be identical to current digital systems with the advantage of having three stereo possibilities when viewing the imagery. Performance issues and data handling issues will still be factors in building efficient production systems.

The rectified Level 1 imagery is already very well geopositioned (controlled) owing to the advanced GPS/IMU system on the aircraft. Both Level 1 and Level 2 rectified imagery, therefore, can be exploited in traditional image processing systems such as those from Earth Resource Mapping, ERDAS, PCI, Research Systems and TNT. The multispectral images yield high quality radiometric data for land-use classification, agricultural analysis, orthophoto production and other classical applications.

REFERENCES

Hinsken L., Miller S.B., Myint Y., Walker, A.S., 1999. Error analysis for digital triangulation with airborne GPS. Proceedings of the 1999 ASPRS Annual Conference, Portland, Oregon, pp. 24-35.

Müller, F. 1991. Photogrammetrische Punktbestimmung mit Bilddaten digitaler Dreizeilenkameras. Deutsche Geodätische Kommission, Series C, Nr. 372, München, FRG, 82 pp.

Zhang, B., Miller, S.B., 1997. Adaptive automatic terrain extraction. McKeown, D.M., McGlone, J.C. and Jamet, O. (eds.), Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision III, Proceedings of SPIE, Volume 3072, pp. 27-36.