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# The State-of-the Art in Airborne Data Collection Systems – Focused on LiDAR and Optical Imagery

CHARLES TOTH, Columbus

## ABSTRACT

Airborne data collection has gone through a paradigm shift in the last decade, moving from a single-sensor-based model to a fully digital multi-sensor suite concept, combining navigation and imaging sensors, and acquiring complementary and many times redundant data in high spatial and growing temporal resolution. During that transition, LiDAR and airborne digital camera technologies have shown equally strong improvements in performance, and state-of-the-art high-end airborne surveying systems incorporate both sensors nowadays.

Airborne LiDAR is probably the most significant technology introduced in the last decade. Based on active sensing, LiDAR systems provide a direct method for acquiring accurate 3D data. In fact, LiDAR quickly gained a significant market share in airborne surveying because of the explicitness of the data; the primary data, the 3D point cloud, requires rather limited processing, depending on application requirements. In particular, LiDAR became the primary source of surface data at the local scale. Improving spatial resolution and point accuracy, however, has broadened the application field, and feature extraction, in particular buildings and vegetation, is rapidly extending. The full exploitation of LiDAR data as well as its characterization is challenging and yet to come.

Airborne digital cameras, including large- and medium-format systems, have shown remarkable developments in the past five to ten years and now represent a mature technology. The state-of-the-art large-format cameras offer unprecedented spatial and radiometric resolution with increasing image capture rates, resulting in performance that supersedes every aspect of former analog film-based cameras by a significant margin. The developments in the medium-format category are also strong; in particular, the spatial resolution and image acquisition rates are increasing steadily. In addition, the field of applications is growing, as performance allows for better coverage and faster, in some cases near real-time, geospatial data extraction. Interestingly, despite the well-established airborne digital camera market, these camera systems are still rapidly developing, as evidenced by a large number of new cameras introduced recently.

This paper provides a brief review of the status of airborne LiDAR and digital camera systems, including major system categories, new applications, performance analysis and future trends.

## 1. INTRODUCTION

Early airborne LiDAR systems were developed in the mid- and late nineties, enabled by two technological developments (Shan and Toth, 2008). First, a suitable scanning mechanism, such as rotating mirrors, became available, and based on previous experiences with laser profilers, laser scanners could be built. Second, a key enabling technology was the introduction of GPS/IMU-based georeferencing systems that allowed for precise platform orientation that was essential to translate the laser range data to accurate 3D coordinates. After a couple of years of mastering the technology, LiDAR systems were gradually accepted and started to show rapid developments. In particular, the last five years have seen significant improvements in terms of increasing point density and in the widespread use of the intensity signal and multiple returns, all combined with better accuracy of the point cloud. Most recently, multi-pulse systems have been introduced to mainstream production.

Large-format airborne digital camera systems were introduced into topographic mapping less than ten years ago, although medium-format cameras in remote sensing applications had been used prior to that date. In the process of transitioning to totally digital mapping technologies, the replacement of the large-format analog cameras by large-format airborne digital camera systems represented the final step. Clearly, the large-format analog cameras reached perfection and were extremely powerful sensors of their time, providing high spatial resolution with large area coverage that were not easy to simultaneously match with digital sensors. Despite strong developments in CCD/CMOS sensor technologies, there is still no single digital sensor that could have an “equivalent” imaging sensor size of an analog camera. Fortunately, there is no need for such a large sensor, as high spatial resolution combined with large area coverage can be achieved by multi-sensor or multi-camera head configurations or a combination of them. Consequently, all the current large-format airborne digital camera systems are based on one of these designs. Although, there are many differences between the two technologies, the most important one is the significantly better radiometric performance of the digital sensors. While digitized film can have, at best, 6-7 significant bits of information, regardless of the actual bits of the A/D converter, CCD/CMOS sensors can provide 10-14 bits of real image intensity, which results not only in better visual appearance but is essential for any image processing tasks (Toth, 2004b).

This paper reviews the digital imaging market, based on sensor designs, and then, the emerging applications that are feasible only for digital systems are considered. Next, a performance analysis of the entire airborne image acquisition system is provided, including both imaging system and georeferencing component. Finally, technological trends and future developments are discussed.

## 2. AIRBORNE LIDAR SYSTEMS

LiDAR technology has advanced significantly in the last four-five years. The ranging accuracy of LiDAR systems has improved substantially, now it is at the 1-2 cm level (1σ) for hard surfaces. Besides obtaining elevation data, the interpretation of the returned signal is now feasible with the appearance of full-waveform LiDAR systems. Point density has improved, as the pulse repetition frequency (PRF) advanced to the 100-200 kHz range. In late 2006, Optech introduced its multiple pulse technology, which allows the firing of a second laser pulse by the sensor before the reflected signal from the previous pulse has been received and detected by the system (Toth, 2004). This has allowed the use of a much higher pulse repetition rate - in this case, 167 kHz - to be reached in the latest ALTM Gemini model. The other market leader, Leica, followed suit and the multipulse-technology-based-Leica ALS60 system features a data capture rate up to 200 kHz at up to 6000 m AGL. Table I summarizes the characteristics of some earlier and most modern airborne laser scanning systems. It is remarkable to note that there are more than 250 airborne LiDAR systems used worldwide; most of the systems are produced by the three major suppliers.

Table I: Airborne laser scanning systems.

| Sensor | Mode | Scan Freq. [Hz] | Pulse Freq. [kHz] | Scanning Angle [º] | Beam Diverg. [mrad] | Pulse Energy [ μJ] | Range Resolution [cm] | Pulse Length [ns] | Digitizer [ns] |
|---|---|---|---|---|---|---|---|---|---|
| **Optech 2033** | Oscillating | 0-70 | 33 | ±20 | 0.2/1.0 | N/A | 1.0 | 8.0 | N/A |
| **Optech 3100** | Oscillating | 0-70 | 33-100 | ±25 | 0.3/0.8 | <200 | 1.0 | 8.0 | 1 |
| **Optech Gemini** | Oscillating | 0-70 | 167 | ±25 | 0.15/0.25/0.8 | <200 | 3.0 | 7.0 | N/A |
| **Optech Orion** | Oscillating | 0-100 | 167 | ±25 | 0.25 | <200 | 2.0 | 7.0 | N/A |
| **TopEye MkII** | Conic | 35 | 5-50 | 14,20 | 1.0 | N/A | <1.0 | 4.0 | 0.5 |
| **TopoSys I** | Line | 653 | 83 | ±7.15 | 1.0 | N/A | 6.0 | 5.0 | N/A |
| **TopoSys II Falcon** | Line | 653 | 83 | ±7.15 | 1.0 | N/A | 2.0 | 5.0 | 1 |
| **Trimble Harrier** | Rotating polygon | 160 | 160 | ±30 | 0.5 | N/A | 2.0 | 4.0 | 1 |
| **Leica ALS50** | Oscillating | 25-70 | 83 | ±37.5 | 0.33 | N/A | N/A | 10 | N/A |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Leica ALS50-II** | Oscillating | 35-90 | 150 | ±37.5 | 0.22 | N/A | N/A | 10 | 1 |
| **Leica ALS60** | Oscillating | 0-100 | 200 | ±37.5 | 0.22 | N/A | 3.0-4.0 | 5.0 | 1 |
| **Riegl LMS-Q560** | Line | 160 | 240 | ±30.0 | 0.3 | 8 | 2.0 | 4.0 | 1 |
| **Riegl LMS-Q680** | Line | 200 | 240 | ±30.0 | 0.4 | 8 | 2.0 | 4.0 | 1 |

## 3. AIRBORNE DIGITAL CAMERA SYSTEMS

The airborne digital camera market has seen notable developments since the first two large format digital camera systems, the DMC from Intergraph (back then Z/I) and the ADS40 from Leica, were introduced at the ISPRS Congress in Amsterdam in 2000. However, the first few years were characterized by pioneering the digital sensor technology, and only a relatively small number of camera systems were introduced; an early review can be found in (Petri, 2003). In contrast, the recent years have seen explosive developments in the airborne digital camera market, including improved performance of existing systems and the introduction of a large number of new camera systems. The following tables list the major commercially available airborne digital camera systems based on their design. Table II shows the basic parameters of area sensor-based large-format camera systems. The DMC, AIC 4x, Quattro and the DiMAC systems are based on multi-camera-head designs, while the UltraCam systems have multi-sensor cameras in a multi-camera-head solution. These camera systems have high-resolution panchromatic and medium resolution color sensing capabilities.

Table II: Frame model based large-format multihead camera systems.

| **Large-format, multihead, frame cameras** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **System** | **Image Size [pixel]** | **CCD Sensor Size [pixel]** | **Number of Sensors** | **Pixel Size [micron]** | **Dynamic Range [bits]** | **Maximum Frame Rate [sec/image]** | **Field of View (FOV)** | **GPS/IMU** | **Software** |
| **DMC**<br>Digital Mapping Camera<br>Intergraph | 13,824 x 7,680 | 7,000 x 4,000 (pan)<br>3,000 x 2,000 (multispectral) | 4 + 4 | 12 | 12 | 2.1 | 69.3° x 42° | Optional Integrated | Any system (frame camera model) |
| **UltraCamX**<br>Vexcel Microsoft | 14,430 x 9,420 (pan)<br>4,008 x 2,672 (MS) | 3,680 x 2,400 | 9 + 4 | 7.2 | 14 | 1 | 55° x 37° | Optional Integrated | Any system (frame camera model) |
| **UltraCam XP**<br>Vexcel Microsoft | 17,310 x 11,310 (pan)<br>5,770 x 3770 (RGB & NIR) | 5,570 x 3,770 | 9 + 4 | 6 | 14 | 2 | 55° x 37° | Optional Integrated | Any system (frame camera model) |
| **DiMAC**<br>DIMAC Systems | 10,500 x 7,200 | 7,216 x 5,412 | 2<br>(2) | 6.8 | 16 | 2.1 | 34° x 26°<br>or<br>66° x 48° | Optional Integrated | Any system (frame camera model) |
| **RolleiMetric AIC x4**<br>Trimble | 13,000 x 10,000 | 7,228 x 5,428 | 4 | 6.8 | 16 | 3 | 60/72/100<br>80° x 65°<br>70° x 45°<br>50° x 30° | Optional Integrated | Any system (frame camera model) |
| **Quattro DigiCAM**<br>IGI-Systems | 13,000 x 10,000 | 7,216 x 5,412 | 4 | 6.8 | 16 | 1.9 | 50/100 mm lens<br>85° x 60°<br>50° x 30° | Optional Integrated | Any system (frame camera model) |

Table III lists the linescanner type cameras, which are based on linear imaging sensors and single camera design. Because of the sparsely populated imaging plane solution, these systems can easily offer identical panchromatic and color resolutions. These systems are quite similar to earth-observing satellite imaging sensor systems. It is important to note that direct georeferencing is crucial for linescanners, as the sensor platform trajectory recovery is nearly impossible just from image data.

Table III: Large-format pushbroom linescanner camera systems.

| **Large-format linescanner cameras** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **System** | **Image Size** | **CCD Sensor Size** | **Number of Sensors** | **Pixel Size [micron]** | **Dynamic Range [bits]** | **Maximum Frame Rate [image/sec]** | **Field of View (FOV)** | **GPS/IMU** | **Software** |
| **ADS40**<br>Airborne Digital Sensor<br>Leica GeoSystems | 12,000 x any | 12,000 (2x) | 3 (2x) + 4 | 6.5<br>(3.25) | 14 | n/a | 64° | Mandatory Integrated | GPro,<br>ORIMA,<br>SocetSet,<br>Virtuozo,<br>KLT Atlas.<br>DIGI3,<br>ImageStation |
| **ADS80**<br>Leica GeoSystems | 12,000 x any | 12,000 | 3 + 5 | 6.4 | 12 | n/a | 64° | Mandatory Integrated | As for ADS40 |
| **JAS150 (HRSC)**<br>Jena-Optronik | 12,000 x any | 12,000 | 5 + 4 | 6.5 | 16 | n/a | 30° | Mandatory Integrated | JenaStereo,<br>SocetSet |
| **4-DAS-1**<br>Wehrli Associates | 8,002 x any | 8,002 | 3 (x3) + 1 | 9 | 14 | n/a | 39° | Mandatory Integrated | Proprietary |
| **SI-250**<br>Startimager | 14,400 x any | 14,400 | 10 | 5 | 9 | n/a | 17°, 23°, 40° | Mandatory Integrated | Proprietary |

Table IV lists the medium-format multi camera head systems, which represent a transition between single-sensor-based and large-format systems.

Table IV: Frame camera model based medium-format multihead camera systems.

| **Medium-format multihead frame cameras** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **System** | **Image Size** | **CCD Sensor Size** | **Number of Sensors** | **Pixel Size [micron]** | **Dynamic Range [bits]** | **Maximum Frame Rate [sec/image]** | **Field of View (FOV)** | **GPS/IMU** | **Software** |
| **SpectraView8**<br>Airborne Data Systems | 8,000x 2,672 | 8,000x 2,672<br>4,000x 2,672 | 2 + 4 | 9 | 12 | n/a | 64° | Optional Integrated | Any system (frame camera model) |
| **DSS 439**<br>Applanix Trimble | 7,216 x 5,412 | 7,216 x 5,412 | 2 | 6.8 | 12 | 3 | 40/60 mm lens<br>62° x 49°<br>44° x 34° | Built in | Any system (frame camera model) |
| **Dual Head Trimble Aerial**<br>Trimble | 7,228 x 5,428<br>8,924 x 6,732 | 7,228 x 5,428<br>8,924 x 6,732 | 2 | 6.8<br>6 | 16 | 1.9<br>1 | 50/80/120 mm lens<br>69° x 55°<br>52° x 40°<br>23° 17° | Optional Integrated | Any system (frame camera model) |
| **Dual DigiCAM**<br>IGI-Systems | 7,216 x 10,000 | 7,216 x 5,412 | 2 | 6.8 | 16 | 1.9 | 50/100 mm lens<br>85° x 60°<br>50° x 30° | Optional Integrated | Any system (frame camera model) |

Finally, medium-format single-camera-head systems are shown in Table V. Note that the STA-1600A 112-megapixel CCD, manufactured by DALSA, used in the SI5 system is currently the largest commercially available imaging sensor on the market, and that this group has shown impressive developments recently.

Table V: Frame camera model based medium-format singlehead camera systems.

**Medium-format singlehead frame cameras**

| System | Image Size | CCD Sensor Size | Number of Sensors | Pixel Size [micron] | Dynamic Range [bits] | Maximum Frame Rate [sec/image] | Field of View (FOV) | GPS/IMU | Software |
|---|---|---|---|---|---|---|---|---|---|
| **SI5**<br>Spectral Instruments | 10,580 x 10,560 | 10,580 x 10,560 | 1 | 9 | 16 | 2 | 74° x 74° | Optional | Any system (frame camera model) |
| **UltraCamL**<br>Vexcel Microsoft | 9,735 x 6,588 | 9,735 x 6,588<br>5,320 x 3,600 | 1+1 | 7.2 | 14 | 2 | 53° x 37° | Optional | Any system (frame camera model) |
| **DiMAC<sup>LIGHT</sup>**<br>DIMAC Systems | 7,200 x 5,400 | 7,216 x 5,412 | 1 | 6.8 | 16 | 2.5 | 34° x 26° or 66° x 48° | Optional Integrated | Any system (frame camera model) |
| **DSS**<br>Applanix Trimble | 5,436 x 4,092 | 5,436 x 4,092 | 1 | 9 | 12 | 2.5 | 40/60<br>62° x 49°<br>44° x 34° | Built in | Any system (frame camera model) |
| **DSS 439**<br>Applanix Trimble | 7,216 x 5,412 | 7,216 x 5,412 | 1 | 6.8 | 12 | 3 | 40/60<br>62° x 49°<br>44° x 34° | Built in | Any system (frame camera model) |
| **DigiCAM**<br>IGI- Systems | 5,440 x 4,080<br>7,216 x 5,428 | 5,440 x 4,080<br>7,216 x 5,428 | 1 | 9<br>6.8 | 16 | 2.5<br>1.9 | 35/40/80<br>69° x 55°<br>52° x 40°<br>33° x 25° | Optional Integrated | Any system (frame camera model) |
| **Trimble Aerial (AIC)**<br>Trimble (Rollei) | 5,440 x 4,080<br>7,228 x 5,428<br>8,924 x 6,732 | 5,440 x 4,080<br>7,228 x 5,428<br>8,924 x 6,732 | 1 | 9<br>6.8<br>6 | 16 | 1.7<br>1.9<br>1 | 50/80/120<br>69° x 55°<br>52° x 40°<br>23° 17° | Optional Integrated | Any system (frame camera model) |
| **NexVue**<br>Spectrum Imaging | 4,080 x 4,080 | 4,080 x 4,080 | 1 | 9 | 12 | 2.5 | 50/90<br>23° x 23°<br>42° x 42° | Optional Integrated | Any system (frame camera model) |
| **RCD105**<br>Leica GeoSystems | 7,162 x 5,389 | 7,162 x 5,389 | 1<br>(1) | 6.8 | 12 | 0.49 | 35/60/100<br>69.7° x 55.3°<br>44.2° x 34°<br>27.4° x 20.8° | Optional Integrated | Any system (frame camera model) |
| **RMK D**<br>Intergraph | 6096 x 6500 | 6096 x 6500 | 4 | 7.2 | 14 | 1 | 45 mm lens<br>52° x 55° | Optional Integrated | Any system (frame camera model) |

In summary, there are several larger companies offering a family of camera products in both large-format and medium-format categories, and a non-negligible group of dedicated system suppliers. Since the airborne digital camera market is experiencing rapid changes, the tables are believed to be accurate at the time of publishing this paper.

## 4. EMERGING APPLICATIONS

The primary applications of airborne surveying did not change with the introduction of totally digital camera systems. Orthophoto production, DEM generation and vector mapping are still the main products obtained by airborne cameras and LiDAR systems. The surface extraction based on stereo imagery has seen a decline, which is mainly due to growing use of active sensors, mostly LiDAR and to a lesser extent IfSAR technologies. However, due to the specific sensor characteristics and the general flexibility of digital systems, including both data acquisition and downstream processing components, new application fields have emerged that were not viable with analog cameras. A few examples, without completeness, are discussed below.

### 4.1 Airborne LiDAR systems

#### Feature extraction

With improving LiDAR performance, increasing spatial resolution and better pulse processing, feature extraction is probably becoming the strongest research direction to support emerging LiDAR applications (Vosselman and Maas, 2009). Compared to image-based extraction methods, the LiDAR point cloud represents a not uniform spatial distribution, many times sparse sampling with respect to the object complexity, carries not textual information and connectivity, but exhibits highly accurate 3D information. Therefore, conventional photogrammetric techniques cannot be directly employed. The key issue to extract features or objects from LiDAR data is the capability of identifying basic shapes and then recognizing the relationship among these primitives. Of particular interest are the extraction of lines and planar surfaces that are essential for building reconstruction and city modeling. There are a variety of methods in computer vision that address simple shape extractions, such as the Hough transform or PCA-based sub-space search, and surface matching techniques, such as ICP. The performance of these methods, however, depends a great deal on the LiDAR point density relative to the object complexity; in other words, whether the average point spacing is an adequate sampling of the object space.

#### LiDAR waveform processing

Although, the point cloud is viewed as the primary LiDAR data, interest in waveform processing is rapidly growing, and thus waveform processing, including sensor level compression, is a key to further exploit LiDAR data. Compared to discrete returns, better object characterization can be obtained from the waveform signal. The difficulty of broader use of waveform is the amount of data, in terms of both storage and processing. In fact, all the state-of-the-art LiDAR systems already acquire waveform data and use them for real-time multiple return generation, but recording only the discrete returns, which are the equivalent of the local peaks in the waveform signal. Suitable compression methods, such as compressive sampling, are essential to reduce the amount of the data stored as well as increased processing power needed to support better waveform processing and compression in real time, and to facilitate faster post-processing. Application areas such as urban mapping and forestry management are the primary beneficiaries of waveform processing.

### 4.2 Airborne digital camera systems

#### City Modeling

The need for city models has started to rapidly grow when Internet giants, such as Google and Microsoft, began to popularize mapping a few years ago. City models require the description of the shape and optical coverage of all the typical city structures, including roads, building facades and roofs, even vegetation, etc. Definitely, high-quality airborne digital imagery is an excellent source for both types of information, although extraction of vertical structures and their optical coverage poses a real challenge. In particular, surface extraction in dense urban areas, where urban canyons can hardly be observed from airborne platforms, is extremely difficult; note that in terms of performance, stereo imagery-based surface extraction practically cannot directly compete with LiDAR technology.

There are three main reasons why high-performance large-format digital aerial imagery can be effectively used for city modeling:

- High radiometric performance is a clear advantage of the CCD/CMOS imaging sensors compared to film. Most importantly, the linear characteristic of the sensor, photons arriving to the sensor are converted to electrons, provides for excellent radiometric resolution, which, in turn, can be exploited in image matching, resulting in a superior performance compared to that of scanned imagery.
- Fast image capture rate allows for increased overlap at virtually no cost, as it only requires additional data storage, which is hardly an issue nowadays. Multiple overlap, however, is essential to produce accurate DEM/DSM surfaces, as multi-ray image matching techniques can be applied. A 2-3 sec frame rate under typical flight conditions can easily provide for 80-90% overlap, and thus, most areas, imaged 5-6 times, can be utilized for multi-ray matching. An additional benefit of the increased overlap is that fewer areas will be without image coverage, which is the typical case in urban canyons with standard 60% overlap imagery.
- Accurate direct georeferencing of the platform trajectory is mandatory for linescanner systems and important for frame cameras too, as it provides for highly accurate exterior orientation data. State-of-the-art georeferencing systems practically eliminated the need for automated aerial triangulation, which is basically used only for QA/QC purposes. Most importantly, accurate sensor orientation along with proper sensor calibration allows limiting the search space for image matching that is essential to achieve both robust solutions and acceptable processing times.

## Oblique Imagery

Oblique imagery is a relatively new application field, which is somewhat similar to city modeling but it primarily caters to non-mapping professionals, who may not need the highest accuracy geospatial data and 3D feature extraction capabilities, but require excellent visualization of their area of interest. The concept of oblique imagery is not new (Petrie, 2008). In fact, the first aerial photos were taken from oblique orientation before nadir orientation, vertical photography became a widely-adopted standard. Figure x shows an analog camera with a configuration that is nearly identical to current oblique camera systems. The recent renaissance of oblique imagery started about ten years ago when Pictometry practically established a new market for it and became the single supplier, currently operating about 100 systems worldwide with partners. The original concept of oblique imagery was to provide imagery that was easier to be understood by professionals who are not in the geospatial field, and, consequently, can relate better to oblique imagery rather than vertical images that they rarely see. With respect to sensor developments, the introduction and the growing use of oblique imagery, however, is quite logical and reflects the fact that to improve the geospatial information processes, data should be observed from different directions with higher redundancy if possible. With an improving performance/price ratio, oblique digital camera systems are becoming more feasible. Note that in a sense the DMC RolleiMetric and DiMAC cameras, which produce a synthetic vertical image, essentially acquire oblique imagery, although with rather small convergence angles. Oblique camera systems are listed in Table VI, and Figure 1 shows an old analog film-based and a contemporary digital oblique camera system.

Table VI: Dedicated oblique camera systems.

| **Oblique camera systems** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **System** | **Camera Heads** | **CCD Sensor Size** | **Number of Sensors** | **Pixel Size [micron]** | **Dynamic Range [bits]** | **Maximum Frame Rate [sec/image]** | **Oblique Angle [°]** | **GPS/IMU** | **Software** |
| **3-OC**<br>Wehrli Associates | 3 | 8,002 | 3 | 9 | 14 | n/a | 45 | Mandatory Integrated | Proprietary |
| **MIDAS**<br>Track'Air | 4 + 1 | 4,992 x 3,328 | 5 | 7.2 | 8 | 2.5 | 30-60 | Optional | Proprietary |
| Pictometry<br>BLOM | 4 + 1 | n/a | n/a | n/a | n/a | n/a | 40 | Built-in | Proprietary |
| **3K**<br>DLR | 3 | 4,992 x 3,328 | 3 | 7.2 | 8 | 2.5 | 35 | Built-in | Proprietary |
| **Dual DigiCAM Oblique**<br>IGI-Systems | 4 | 7,216 x 5,412 | 4 | 6.8 | 16 | 1.9 | 45 | Optional Integrated | Any system (frame camera model) |

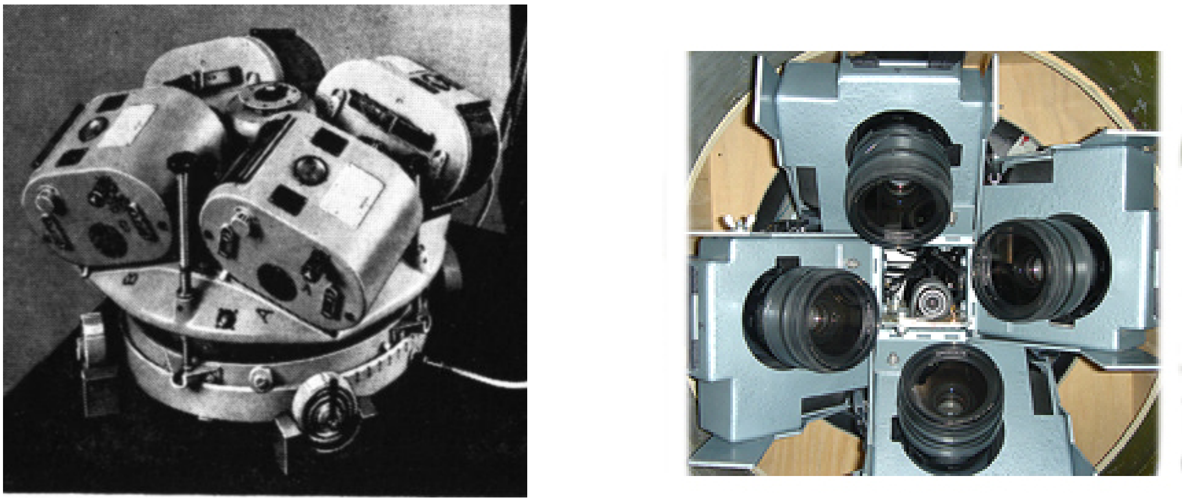

(a) (b)

Fig. 1: (a) Zeiss four-coupled oblique film cameras from the 1930s, (b) BLOM oblique camera system.

## Rapid/Emergency Mapping

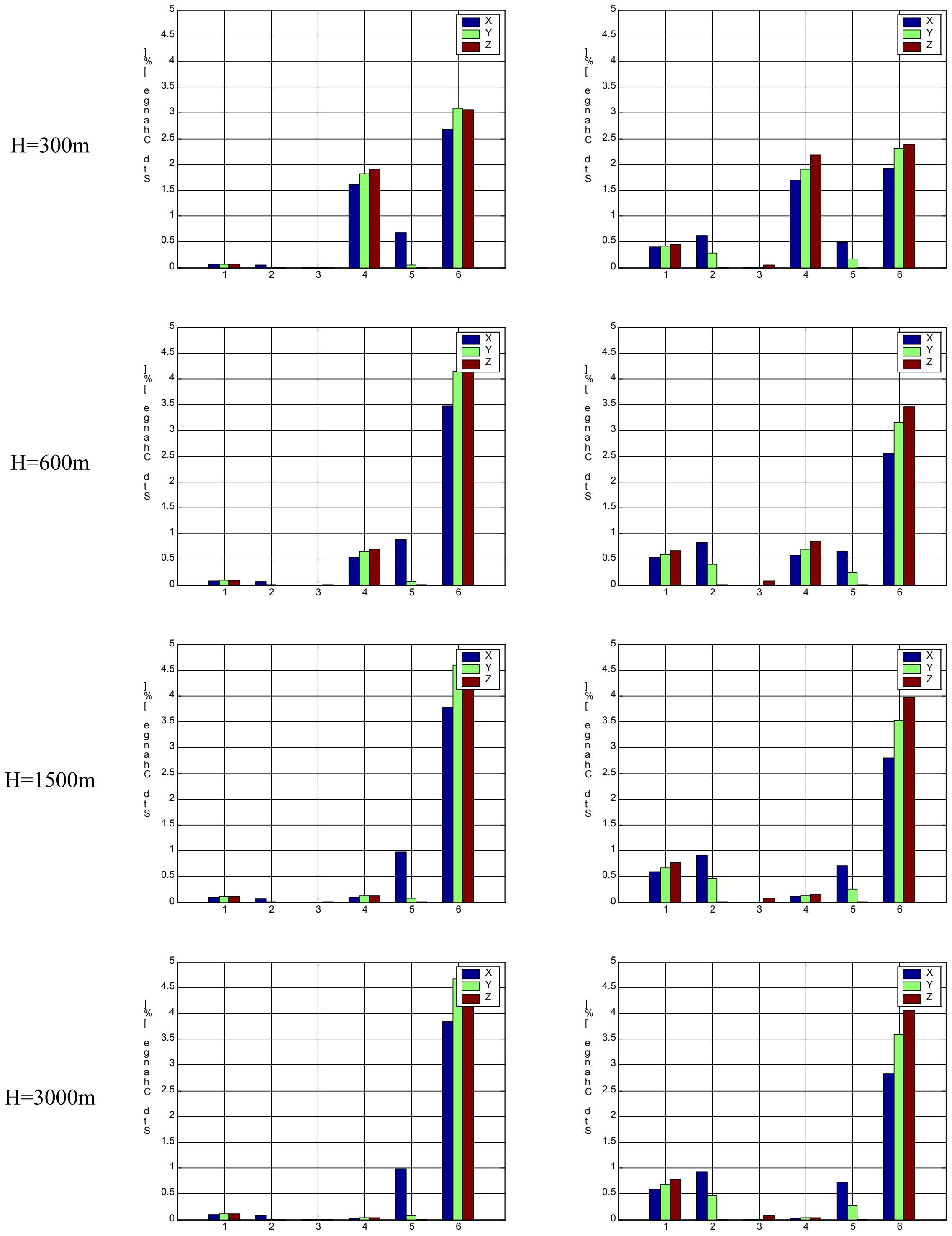
The need for faster and more recently near real-time or even real-time data acquisition and processing is steadily growing. On one side, technological developments are the driving force, as they provide the foundation for such systems. On the other side, recent natural and man-induced disasters, such as the 2004 tsunami in East Asia, Hurricane Katrina in New Orleans in 2005, the Sichuan earthquake in China in 2008, and the 9/11 terrorist attack in New York, further reinforced the need to develop dedicated mapping systems and deploy them regionally. Clearly, fully digital systems are the only choice in terms of technology, and high-performance digital cameras represent the primary choice for optical coverage. It is important to note that conventional geospatial data users also demand shorter delivery times.

Fig. 2: DLR 3k dedicated camera system from German Space Agency, based on 3 Canon EOS digital cameras; also seen is the IMU sensor (orange).

The capability for rapid deployment and near-real time or real-time operation can be exploited in an emerging application such as traffic monitoring. The development of the road network simply cannot keep up with the steadily increasing number of vehicles worldwide; thus to obtain traffic flow data in real-time is essential to improve traffic management. Airborne surveying represents a complement to the existing ground sensor-based network, offering the advantage that it can be deployed almost anywhere. On the platform side, it should be noted that UAS (UAV) are deployed in increasing numbers, although their widespread use is primarily held back by institutional matters (legal). Figure 2 shows an oblique camera system, developed by DLR to support traffic flow data acquisition.

## 5. PERFORMANCE ASSESSMENT OF AIRBORNE DIGITAL IMAGING SYSTEMS

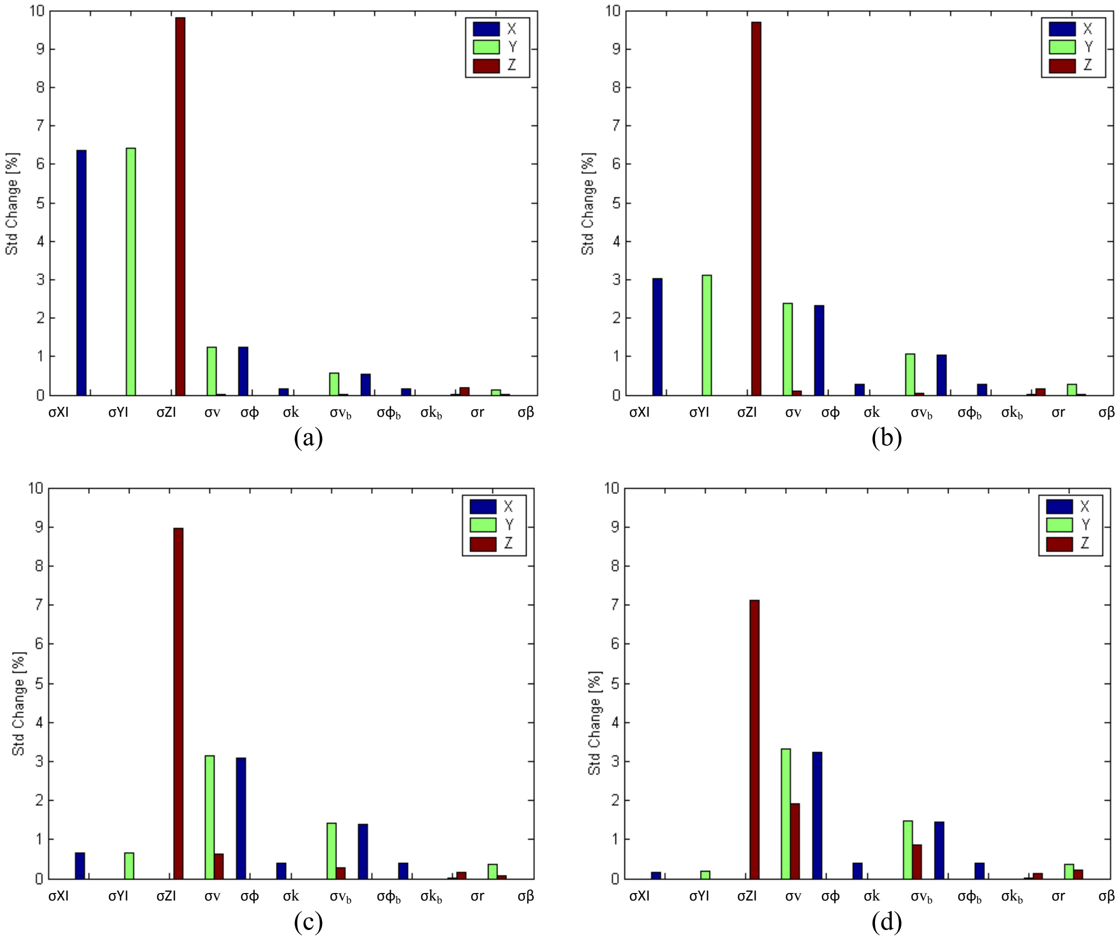
The ultimate performance measure of any airborne digital camera system is the 3D point positioning accuracy that can be achieved under given circumstances. Therefore, the entire system, including imaging sensor, georeferencing component, flight conditions, etc., should be jointly considered, and not only the camera sensor parameters, to assess the overall 3D point positioning performance. The error characteristics and the general performance of the imaging sensors have been of interest, and, in particular, both digital cameras and LiDAR systems are extensively researched regarding their ultimate limits, as well as what can be realistically achieved in production. For digital cameras, there is an additional distinction between manual and automated processes with respect to feature extraction accuracy. Obviously, the sensor calibration is the first item of the error budget, and extensive tests have been carried out by various groups. The most notable recent camera calibration effort is the EuroSDR supported investigation, see (Cramer et.al., 2008). A joint comprehensive analysis of digital camera and LiDAR systems can be found in (May Csanyi, 2007), and performance results for typical airborne surveys are illustrated in Figures 3 and 4 for digital cameras and LiDAR, respectively, showing the contributions of the different sensors and system components.



(a) DMC (b) RMK D

Fig. 3: Error budget distribution of the DMC and RMK D cameras; 1: image measurement accuracy, 4 μ for both imagery, 2-3: principal point and focal length accuracy, 3.5μ and 5μ, 4: position accuracy, 5cm horizontal and 7.5cm vertical, 5-6: boresight misalignment and attitude accuracy, 15”, 15” and 30”.

Figure 3 compares the relative error budget of the DMC and RMK D systems, at four flying heights. As the figures indicate the relative importance of the various error source changes with flying height. In general, for lower flying heights the precision of the aircraft position is the dominant factor determining the point positioning precision, while for larger flying heights the platform attitude angle precision followed by the image coordinate measurement standard deviation dominate the error budget, clearly indicating the difference between the two cameras due their different spatial resolution.



(a) (b)

(c) (d)

Fig. 4: Accuracy analysis bar chart for high-end LiDAR system with high-performance georeferencing system for typical flying heights: (a) H=300 m, (b) H=600 m, (c) H=1500 m, (d) and H=3000 m.

Figure 4 shows the error budget of state-of-the-art LiDAR systems. The relative influence of the various error sources significantly depends on the flying height and also on the scan angle. Figures 4a-4d show the accuracy bar charts for 10° scan angle and flying heights 300 m, 600 m, 1500 m, and 3000 m, respectively for a system that has $\sigma_X = \sigma_Y = 5$ cm, $\sigma_Z = 7.5$ cm, $\sigma_v = \sigma_\varphi = 15$ arcsec, $\sigma_k =$ 30 arcsec, boresight accuracy: $\sigma_{vb} = \sigma_{\varphi b} = 10$ arcsec, $\sigma_{kb} = 30$ arcsec, ranging accuracy: $\sigma_r = 1$ cm, and scan angle accuracy: $\sigma_\beta = 5$ arcsec. The height of the bars gives an indication of the percentage change in the point positioning precision in the three coordinate directions when the precision of each random variable increases by 10%. As the figures indicate the relative importance of the various error source changes with flying height. For smaller flying heights the precision of the aircraft position is the dominant factor determining the point positioning precision. For example for 300 m flying height, a 10% change in *X, Y, Z* position standard deviation results in about a 6.5%, 6.5%, and 9.8% change in the precision of the determined *X, Y, Z* point coordinates on the ground, respectively; while the same change in aircraft attitude angle standard deviation results only in about a 1% or less change in the point positioning precision. For 3000 m flying height, the aircraft position precision change has a very small effect on the positioning precision (except for the vertical aircraft position accuracy change that still has a more than 7% effect on the vertical coordinate precision), while the attitude precision change has a much higher effect on the point positioning.

## 6. TRENDS IN AIRBORNE DIGITAL IMAGING SYSTEMS

Comparable sensor and system developments are expected in both passive and active imaging technologies, mainly because the technology they are based on is practically identical, except for the sensors themselves, and, equally importantly, the demand for geospatial data is growing strongly.

### 6.1 Sensor developments

In the past ten years, laser pulse rate, the primary parameter to increase the point cloud density of airborne LiDAR Systems, has shown a nearly linear trend. Once the limits imposed by the pulse's travel time were reached, multi-pulse systems were introduced. From this point, the laser pulse rate is expected to continue to increase for many years to come, provided the advancements in laser supply or just using multiple laser sources, such as the twin QL-560 configurations from Riegl.

As mentioned above, airborne digital camera systems are still feverishly evolving, in fact, at a surprisingly quite fast rate. Therefore, any prediction concerning future directions is rather difficult. Definitely, sensor technology developments continue to impact the design of airborne digital camera systems, although the market is too small to support dedicated CCD/CMOS developments. Fortunately, the strong consumer and industrial camera markets jointly drive sensor developments. The first 16 Mpixel CCD sensors were introduced by Kodak and Fairchild in the mid-nineties and cost about 10-20 times more than a complete professional camera system with 17 Mpixel CMOS sensor, which is used in the DLR-developed system. Most notably, not only the price, but also the difference in performance is astonishing. The CCD/CMOS sensor technology is currently at the 50 Mpixel level, which is quite adequate to support the medium-format camera market, such as the RMK D, RCD105, DSS, Rollei AIC, etc., systems. In addition, the chips with increased size, installed in large-format digital camera systems can further improve camera resolution, as in the case of the UltraCam family, with the D, X and XP members.

### 6.2 Georeferencing component

Supporting technologies are essential for data processing of the imagery, and include the georeferencing component (sensor platform and ground), communication links, and overall computer processing capabilities. Direct georeferencing is an essential enabling technology for line scanner cameras, and offers significant economic benefits to frame camera model-based systems, so it is standard on all high-performance systems. Current state-of-the-art georeferencing systems are based on GPS and IMU integration and the solution is post-processed using a single baseline. This is expected to change soon, as the CORS network is rapidly growing in the developed world, and a network-based solution could be used, offering clear benefits, such as no limitation on the baseline and improved and consistent performance. For surveys in areas without a CORS network, PPP technology could be a consideration, which is based on using direct error modeling, provided by IGS worldwide. Table VII lists the currently available GPS solutions.

Table VII: Available GPS solutions.

| | **Accuracy** | **Real-time/Post-processed** |
|---|---|---|
| **Pseudorange** | 10 m-level | Post-processed |
| **Pseudorange-based differential** | m-level | Post-processed |
| **WAAS pseudorange** | m-level | Real-time |
| **Differential with base station** | cm-level (*) | Post-processed/Real-time |
| **Differential with network solution** | cm-level | Real-time/ Post-processed |
| **Satellite based differential correction** | sub-m level | Real-time |
| **RTK** | cm-level | Real-time |
| **VRS** | cm level | Real-time |
| **PPP** | sub-dm level | Post-processed |

(*) baseline-dependent

An important aspect of the georeferencing solution is whether it is available in real-time or postprocessed. Until recently only postprocessing has been the practice if high accuracy is required. However, technology is at the point that real-time solutions are becoming feasible even at high accuracy; note that Omnistar has provided for submeter GPS positioning for many years. GPS corrections at the centimeter level, however, have been offered just recently and mostly for applications with terrestrial sensor platforms. For example, the use of VRS on the ground is rapidly growing and it could be easily deployed to an airborne platform by available communication links. Since VRS is based on a network solution (CORS), the performance is consistent over large areas. Therefore, the practice of smoothing, combining forward and backward navigation solutions, offers no advantage in terms of achieving better accuracy of the sensor platform.

GPS performance is fundamental for accuracy of GPS/IMU-based direct georeferencing, and therefore, GNSS developments should be mentioned, as alternative satellite-based navigation systems to GPS will be introduced in the future, including Glonass, Galileo, Compass, and a few regional ones, such as QZSS, IRNSS, DORIS. However, their impact in terms of accuracy and performance is practically negligible on airborne platforms with good sky visibility and low multipath.

### 6.3 Algorithmic developments

Algorithmic and software developments in airborne geospatial data processing are generally predictable, as progress is relatively proportional to time since digital photogrammetry was introduced in the early 90's. In particular, image matching, the central piece of many methods, has reached a high level of performance, including accuracy and robustness. Furthermore, from the two basic steps, coarse matching and refinement, the first part has been greatly simplified by the use of direct georeferencing, as it significantly constrained the search space (earlier matching was used to recover sensor orientation). In that context, for matching between images of quite different geometry, such as oblique and vertical imagery, and of different sensors, SIFT can provide a robust solution for coarse initial image coregistration, as a substitute for direct georeferencing. It is important to note that the general matching performance is superior to human operator-based measurements. Image matching is the foundation of many basic photogrammetric processes, such as aerial triangulation, sensor calibration, surface extraction, etc. The next step in image matching is likely to be real-time implementation, which is simply an implementation issue of how to channel the data in real time to a processor or multiprocessor system that has enough computing power. In addition, multi-image matching will further spread, as highly redundant images become more available. High-level feature extraction and object recognition tasks will continue to improve but they will stay in the postprocessing mode for the foreseeable future. The processing of direct 3D data, such as LiDAR, and multiray-derived surface points from high-overlap airborne imagery will further advance, and, in a sense, the gap between the two technologies will decrease, in particular, as more advanced feature extraction and object recognition methods are developed.

## 7. CONCLUSIONS AND OUTLOOK

In the last decade, large-format airborne digital camera systems have been perfected to a performance level that supersedes analog camera systems by a convincing margin. In addition, they offer advantages that have been widening their application field and keep these systems competitive with other sensors and geospatial data acquisition technologies. Despite the well-established market, it is striking to see the still intense ongoing developments, resulting in the introduction of several newer systems recently.

LiDAR systems, in general, laser scanning technology continues to advance, following similar trends to remote sensing imagery developments, where the past gaps between terrestrial, airborne and spaceborne imagery are not only disappearing, but the overlap between the imagery acquired from various platforms is growing. In addition, LiDAR technology, the primary source of surface data at the local scale, is likely to extend to the feature extraction field, as point cloud density continues to increase.

In summary, sustained developments are expected in airborne LiDAR and digital camera systems, including both large-format and medium-format categories. The market share of oblique imagery is anticipated to grow, the integration between the two technologies will continue, and, finally, dedicated airborne imaging systems will likely see even stronger developments.

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