

Flying the New Large Format Digital Aerial Camera Ultracam

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ABSTRACT

The race to replace the aerial film camera started in July 2000 with the product announcements of the ADS-40 by LH-Systems (now Leica Geosystems) and of the DMC by Z/I Imaging. Recently, the UltraCam-D was introduced. This is a 90 Mpixel large format aerial camera by Vexcel Imaging to add an innovative offering with a focus on a on-on-one replacement of aerial film cameras. This is achieved by the continued use of an unchanged work flow, very much as if the digital image had not been obtained from a digital camera but by scanning a film image, yet with dramatic economic advantages as well as with the added benefit of a smooth all-digital operation. While this “unchanged workflow” is an initial value of the new system, it nonetheless offers numerous opportunities for improving the current state-of-affairs of photogrammetry, as much so that one could speak about a “paradigm shift”. The most important opportunity is the ability to dramatically increase the forward overlaps in photogrammetric surveys without any added cost, and producing a much higher level of automation in photogrammetric data analysis. Photogrammetric software will have to be adjusted to go from current stereo, thus “2-ray photogrammetry” towards multi-eye, thus “multi-ray” solutions.

1. DIGITAL CAMERA TECHNOLOGY

1.1. Film Is Being Replaced by Digital Sensors

Consumer and professional photography are in a rapid transition towards fully digital sensing. Single CCD arrays are being combined with single lenses into relatively straightforward digital camera solutions. At the same time, cellular telephony and the web are adding instant cameras based on CMOS-sensors. Digital visual information sensing and processing are rapidly becoming ubiquitous phenomena of a much wider importance than ever envisioned in the past.

Map-related sensing has been digital onboard satellites from the early days of planetary imaging in 1964. Space-based remote sensing systems are strictly digital from the sensor to the image archives and final information products. Aerial mapping, in contrast, is hesitating to go all digital. In spite of film scanning being available and well introduced since more than 10 years, typical photogrammetric operations are still predominantly analog and analytical, with the exception of ortho photo production. It is obvious that ortho photos would simply not be feasible at any reasonable quality and cost, were it not for digital procedures. Yet all new film, while often scanned, is stored in traditional roll film archives and the digital data often get deleted after ortho photos have been delivered.

1.2. Digital Aerial Camera Needs

Aerial photography is a compromise between efficiency in aerial operations, requiring a minimum of flight lines, and technical feasibility, with as large an image format as possible without compromising image quality. Over many decennia, the film format at 23 cm x 23 cm has emerged as that compromise. It maximizes the field-of-view on the ground, thereby minimizing the number of flight lines to be flown for a specific project area. Aerial digital sensing needs to obtain similar efficiency in aerial operations to be competitive with traditional film. At issue is less the cost per flight line, but more the duration of weather-sensitive flight operations and the difficulty of getting

an area imaged before light conditions deteriorate and the weather turns. The field-of-view of a digital camera needs to be as large as that of a film camera to successfully compete. “Field-of-view” is, however, expressed in number of pixels across the swath. We believe that 11,500 pixels contain more information than 23 cm of aerial film. This implies that a 20 μ m digital pixel is better than a pixel scanned from film, at any size.

Making the transition to digital sensing easy on the photogrammetric user results in a need to produce images in a format that is identical to scanned film. Producing a centrally perspective geometry with a single perspective center for each image, and presenting the result in 8 bits per color channel will ensure that existing workflows can be continued.

Yet the digital sensor needs to provide significant advantages over film. We will discuss these later. But at least one “killer advantage” is needed to have a hope of replacing film forever. And this clearly is the elimination of all costs for consumables such as film and film processing, plus the elimination of scanning expenses.

1.3. UltraCam Technology

The race to build a successful replacement for aerial film cameras requires as its main challenge an ability to obtain a large field-of-view with a large number of pixels across the swath. Many concepts have been invented and have been submitted for patent protection which promise a large format image (Gorin et al., 2002; Teuchert & Mayer, 2000; Goetz, 1980; Hinz et al., 2000; Leica, 2002; Z/I Inc, 2002; Positive Systems, 2001; Neukum et al., 2001). Yet the solution must be simple enough to avoid excessive cost. It also must be environmentally stable against changes in temperature or vibrations, and it must produce geometrically accurate, thus photogrammetric images with a radiometric performance reflecting the advantages of digital sensors. Finally, it must create an image in a short period of time, preferably in a sub-second time interval.

Because this is a difficult problem, some solutions for digital aerial imaging have been proposed that work with smaller format cameras (Enerquest, 2002; Emerge, 2002). Yet these solutions do not minimize the number of flight lines, they do not maximize photogrammetric efficiency.



Figure 1: The sensor unit of the UltraCamD large format digital aerial camera. Other system components are the storage and computing unit and the interactive interface.

The UltraCam solution consists of a sensor unit seen in Figure 1, an on-board storage and computing unit, an interactive on-board monitor and software. The design uses multiple area array CCD sensors, and 4 lenses (optical cones) for the high-resolution panchromatic image (see the 4 linearly arranged cones in Figure 1). Each optical cone has the same field-of-view, but has its CCDs

placed in a different position in the focal plane. A large image is built from combining the 4 separate component images, using one cone as the “master” to define the image coordinate system. The approach is capable of producing any size image that can be meaningfully resolved by the lenses, by simply using the appropriate number of CCDs in each of the four focal planes. We opted for a format of 11,500 by 7,500 pixels based on 9 individual CCDs, each producing a sub-image with 4K by 2.7K pixels. One can easily show that increasing the number of CCDs to 16, still employing only 4 lenses can produce a 15,400 x 10,000-pixel image.

Additional optical cones produce color separates in red, green, blue and near infrared, as seen in Figure 1 with the 4 four eccentrically placed lenses.

1.4. UltraCam Specifications

Table 1 summarizes the technical specifications of the camera. It is useful to note that the physical pixel size is a mere 9 μm , the lens focal length is 100 mm. As a result one has a camera that is much smaller in size than the equivalent 23 cm x 23-cm format of the film camera with its 210 mm lens. Noteworthy is the availability of forward-motion compensation (FMC) by means of time-delay integration, permitting one to use long exposure times in dim light conditions. Exposures can be at 2 msec up to 17 msec.

Table 1: Specifications of the UltraCam-D digital aerial camera.

Sensing Unit

Panchromatic image format	11500 * 7500 pixel @ 9 μm , 103.5 mm * 67.5 mm
Lens system focal distance and aperture	100 mm, f 1/5.6
Field of view cross/along track	55° / 37°
Multi-spectral (RGB, NIR)	4,008 * 2,672 pixel, @ 9 μm
Shutter, seconds	1/500 – 1/60
FMC	TDI controlled
Frame rate	1.3 frames / second
Radiometric resolution	> 12 bit
Dimensions	45 cm * 45 cm * 60 cm
Weight	< 30 kg

Storage & Computing Unit

Storage Capacity	> 1.5 TB
Uncompressed Frames	> 2775 frames
Dimensions	55 cm * 40 cm * 65 cm
Weight	< 35 kg

A single mission will currently collect up to 2775 individual full frames, twice recorded for redundancy, using 28 mobile hard drives with 60 Gbytes each. As storage technology progresses, the current hard drives may be easily swapped against larger ones, thereby increasing the number of full images to be collected in one mission. Expect that by 2005, single missions will produce 10,000 or more images at no extra cost, simply letting the Moore-principle do its magic.

The interval between two images can be 0.75 seconds. Suppose that urban mapping imagery is being collected with a pixel size of 3 cm and a forward overlap is needed of 80% to minimize occlusions behind buildings and to maximize success of automated procedures. To achieve this overlap at an air velocity of 60 meters per second one will need to image at an interval of 0.75 seconds. This rate is highly useful and an advantage of digital sensing, especially at larger scales.

2. DIGITAL VERSUS FILM SENSING

The digital sensors have advantages over film due to the absence of grain noise, due to the dynamic range at 12 bits per pixel as opposed to <8 bits in film, and due to an inherent geometric stability because of the absence of moving elements and of photo laboratory processes.

2.1. Laboratory Analysis

We have previously presented results of various laboratory studies of the differences between film and digitally sensed images. Figure 2 illustrates such results obtained with a Siemens star. It becomes evident that at the nearly identical ground sampling distance of 0.4 mm, the digital image resolves more detail than the scanned film by a factor of almost 2 (the critical radii of resolution are 265 μ m versus 145 μ m).

Another laboratory test concerns stereo matching. Figure 3 derives from Perko & Gruber (2002) and shows that stereo matching may be a factor 2.5 better with a digitally sensed image pair than with scanned film.

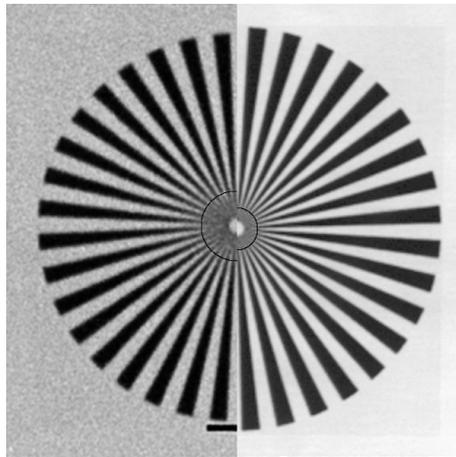


Figure 2: The Siemens star imaged onto film (left) and onto a digital sensor (right), both with a GSD (ground sampling distance) of 0.4 mm. The critical radius in the left segment is 265 μ m, on the right image it is 145 μ m (see also Leberl et al., 2003 and Leberl et al., 2002).

2.2. Aerial Considerations

Figure 4 illustrates that aerial imagery taken with a digital sensor contains more detail than film. This is supported by the absence of notorious grain noise and a 16 times higher radiometric range. The grain noise appears to be like a „veil“ placed over the terrain and obscuring the detail under it.

The stereo matching experiment will confirm its conclusions also when applied to aerial data. As shown by Gruber et al. (2003), film will lead to disintegrating matches if the scans are at a pixel size that shows the grain. Digital images will match successfully and with high correlation values in featureless terrain, where film images can no longer produce a good surface definition.

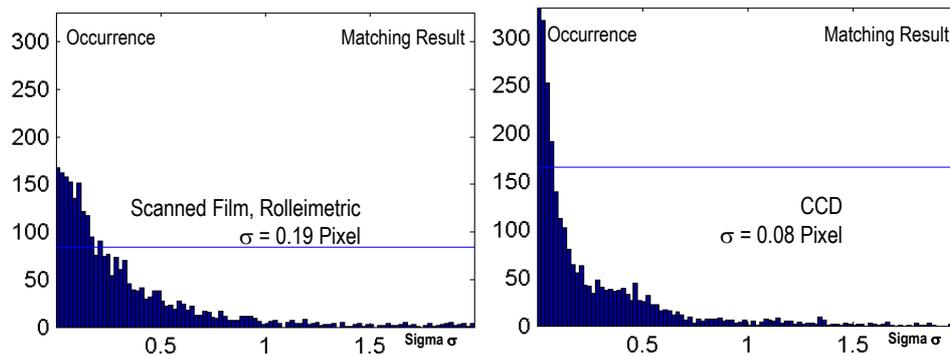


Figure 3: Stereo matching experiment using scanned film and a digital sensor. Note that the matches with the digital sensor have a noise level 2.5 times smaller than that of the scanned film (from Gruber et al., 2003).

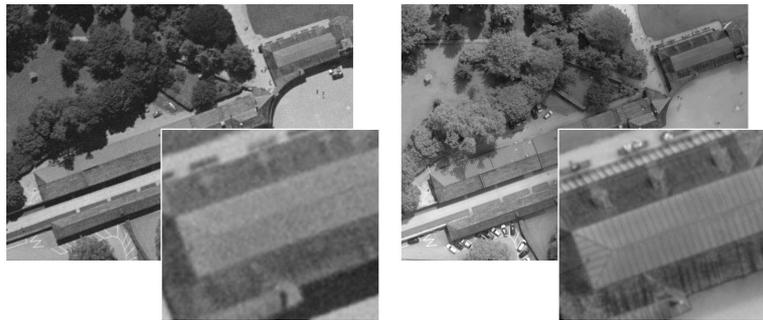


Figure 4: Comparing aerial film and digital image. Left is scanned film at a pixel size of $15\ \mu\text{m}$ (GSD of 15 cm); at right is the digital image with a GSD=17cm (from Leberl & Gruber, 2003).

3. FLYING THE ULTRACAM CAMERA

A prototype camera has been in successful operation all throughout 2003. On its routine flights it has produced a repository of sample imagery used in various publications. Figure 5 presents a sample index map of a block with 2 strips and 14 individual large images. The digital „scale“ was 1:10,000. This implies that the 100 mm lens was flown at a flying height of 1000 m. The resulting GSD is about 9 cm, given that the physical pixel size on the focal plane is $9\ \mu\text{m}$. While scale does not mean much in digital images and GSD means everything, this can be used to relate the digital images to traditional film. The GSD of 9 cm per pixel is obtained from film if flown also at 1000 m flying height, using a 210 mm lens. However, this will produce a film scale at 1:4,700. If the film gets scanned with $20\ \mu\text{m}$ pixels, this will produce a GSD of 9 cm, the same that was obtained with the digital camera flown at the same flying height. It is relevant to note that the 9 cm UltraCam-pixels were obtained with an exposure time of 8 msec. An airplane flying at a speed of 70 meters per second will move 56 cm during the exposure time. Therefore the FMC needs to get activated to remove the image blur that would otherwise occur at a 9 cm GSD.

Note that each digital image has a format of $11,500 \times 2,700$ pixels. This is the format of the prototype sensor. The black edges in each image delineate the format and make it easier to review the arrangement of the block. A full format frame is shown in Figure 6. It is obtained by stitching multiple CCD-array images into one single image. However, the 2 outside arrays are obtained through one lens, while the center area is obtained from a second lens. Figure 7 presents the result of stitching removing all differences between overlapping image segments by means of a projective transformation of the slave image (the center area) into the master image (consisting of the two

outside sub-frames). Matching needs to cope with fewer differences than in the stereo application: the overlapping images are identical in geometry. Therefore, a matching accuracy in the range of ± 0.1 pixel is achievable, representing $\pm 1 \mu\text{m}$ on the image.

Color is added to the panchromatic image in a „coloration“ process. The 4 color bands are matched with the panchromatic image and then up-sampled to add 4 color values to each panchromatic pixel. The process is also denoted sometimes as „pansharpening“. Coloration must not change the physical color measurement values if the resulting images are being subjected to an automated classification.



Figure 5: Block of UltraCam imagery in two strips of an area near Salzburg (Austria). The ground sampling distance GSD is 9 cm. Using the 100 mm lens, the flying height is 1000 meters. The image format in this prototype data set is at 11,500 x 2,700 pixels. The black lines serve to mark the individual images.



Figure 6: A single image from the prototype camera at 11,500 x 2,700 pixels, taken from the block in Figure 5, composed from 3 separate CCD recordings used in 2 optical cones.



Figure 7: Illustrating the stitching of separate image segments. At the left and right are segments from two component images to be stitched, showing their overlapping region of about 250 pixels. The center shows the seam after stitching is complete. This is taken from Figure 6.

4. SYSTEM INTEGRATION ISSUES AND DATA FLOW

4.1. Deliverable System

The UltraCam is meant to replace the aerial film camera. This would imply that the film camera environment remains available since the film component will be swapped against a digital camera. The mount, the flight management, the direct geopositioning support all remain available in that case. The digital sensing system needs to be compatible with existing mounts, flight management systems and geopositioning support. It is clearly a requirement for the camera to be compatible with a complex pre-existing airborne environment.

However, initially digital sensors will fly and film cameras will fly as well. Workflows will be maintained for both systems in parallel. In that case the UltraCam needs to get equipped with a new mount, a new flight management system and geopositioning support. The delivery of the camera includes these components as an option. For example, IGI's CCNS-4 and AeroControl system are available with the UltraCam, and the gyrostabilized mount GCM, also of IGI, is an optional deliverable.

4.2. Synchronous versus Syntopic Image Triggering

The camera has a master cone, which defines the image coordinate system. The slave cones can be triggered synchronously with the master cone. Were this to happen, one would produce slave images with separate principal points from separate airborne positions of each cone. Conventional wisdom has no alternative to this mode of image acquisition and argues that the effect is negligible.

The UltraCam offers another innovation in the manner in which the image gets triggered. Optionally, the camera operator can select the „syntopic“ trigger mode. Note that in this mode the master and slave cones have all the same principal point in 3D space. The name of this mode is by a new word: „syntopic“ („topos“, Greek for „the place“). Figure 8 explains this alternative image acquisition mode. It implies that one employs the airplane's motion to one's advantage. Each cone gets triggered at exactly the moment when its entry pupil is in the same location. Since the physical cones are set about 7 cm apart, they need to be delayed by 1 msec from one another, assuming that the flight velocity were at 70 m /second.

4.3. Data Flow

The disappearance of film results in the need to treat the digital data with great care. The airborne operation produces so-called „level-00“ image data that need to get converted to seamless „level 3“ images for delivery to customers. Intermediate levels 0, 1 and 2 are of internal importance. In the UltraCam solution, data processing is available in 4 alternatives. The on-board storage and

computing unit operates with its 15 mobile processors in the air, on board in the parked plane on the ground, or the unit can be taken off the airplane and continue operating in a hotel room or in the home office. The software running on the storage and computing unit is also operating on the home office network.

Transfer of the images from the storage and computing unit is onto a „mobile server“ with firewire disks which serve to get shipped to the home office or customer sites. Final image products get archived and cataloged in a new product called Earthfinder-Aerial, available with the camera.

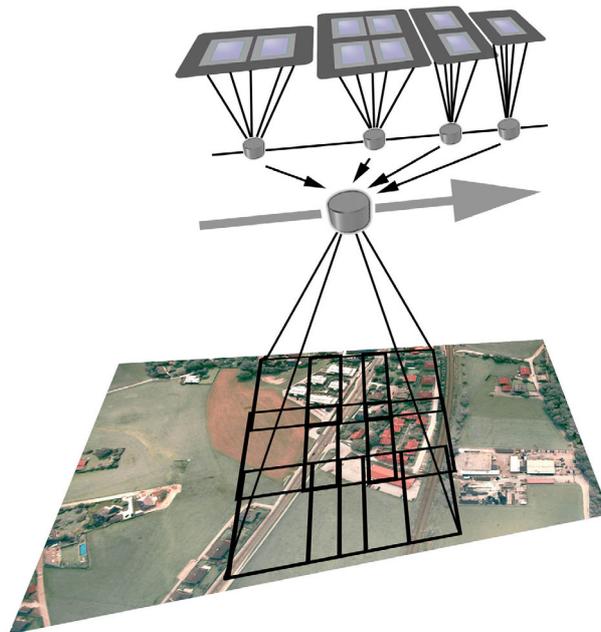


Figure 8: Explaining the difference between „synchronous“ and „syntopic“ image acquisition. The synchronous mode triggers all 4 separate cones at the same time. The syntopic mode triggers them at an interval defined by the flight velocity, about 1 msecond apart.

4.4. Flying at High Forward Overlaps

The traditional photogrammetric workflow is based on 60% forward overlaps. Stereo operations strictly employ 2 intersecting projection rays, thereby committing a „sin“ against the required use of sufficient redundancy. With the advent of digital sensors, the number of images is no longer a factor of the project costs, as long as processing is automated. This encourages thinking about the use of higher than 60% forward overlaps. The fact that the UltraCam will initially already be able to collect 2775 images per mission supports routine use of 70% and 80% forward overlaps in almost all circumstances. Smaller urban mapping projects might benefit from the use of 90% or even 95% forward overlaps. The aero-triangulation will become more robust since mismatches of tiepoints will disappear. DEMs will also be without mismatches and all terrain segments will have coverage.

An integrated system with geopositioning tools and multi-ray photogrammetric processing will result in a *DEM-robot* and will also produce true orthophotos robotically.

5. CONCLUSIONS

We have introduced the UltraCam, a novel digital aerial camera. It has a format of 11,500 x 7,500 pixels and can collect almost 3000 images per flight. We have argued that the time of digital aerial sensing has come and that the time of photogrammetric film cameras is ending. The primary killer advantage of digital cameras is economical: savings of film, photo processing and scanning are covering the cost of the camera. In addition there are numerous added benefits: examples include simultaneous true and false color, better radiometry, absence of grain noise, faster image repeat cycles, uncompromised geometry, better results in automated procedures, instant quality control during image acquisition, better stereo quality and a no-cost option to increase the forward overlaps at will.

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