Novel Concepts for Aerial Digital Cameras

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Abstract
Aerial film cameras are highly standardized measuring systems. The race is on to find a digital successor applicable as a photogrammetric measuring device with clear advantages over film, meeting accepted standards, covering a large field-of-view, maximizing the geometric resolution of terrain surface detail, minimizing the number of flight lines. Some of today's digital cameras have a small format at a relatively low resolution for special applications. High expectations are associated with the ADS40 by Leica Geosystems (Leica, 2002) using multiple linear arrays in a push-broom mode in analogy to multi-spectral satellite remote sensing systems. Finally there exists the DMC by Z/I Inc. with multiple square arrays CCDs which are assembled into a large "virtual image" as explained by Z/I Inc (2002). We argue that these digital camera concepts are not replacing the existing film cameras. They have limitations as "photogrammetric measuring sensors" and they require a workflow that deviates from the established photogrammetric processes. We argue that the desired digital aerial camera will produce metric imagery as if it had been obtained from a traditional film camera and photogrammetric precision scanner, but at advantageous radiometric performance, advantages in the image acquisition and without the cost of film or film scanning.

1. DIGITAL IMAGES IN PHOTOGRAMMETRY: SCANNING OF FILM IMAGES

1.1 From Orthophoto to Digital Stereoscopy

The transition from analytical to digital photogrammetry was encouraged by the rapid acceptance of low-cost digital orthophotos (ISPRS-Amsterdam, 2000). Since then, all phases of photogrammetric operations have become digital, particularly the creation of terrain models by digital stereoscopy. However, film remains the only significant source for aerial metric images, for the time being. Pixel arrays for digital photogrammetry are obtained by scanning conventionally produced film images.

1.2 Preserving the Film's Geometric Performance

Highly standardized aerial film cameras produce images at a format of 23cm x 23cm with an inner geometry that is calibrated to within ± 2 µm and encoded into fiducial marks on each image. The system resolution of an aerial camera is determined by its optics, the film, by the available illumination from the sun and the effect of camera motion. The result may be at times within 40 line-pairs per millimeter (25µm /lp).

Photogrammetric scanning transfers this geometric accuracy and resolution into the digital domain. Photogrammetric scanners therefore are designed to produce errors of less than ± 2 µm and produce pixels in the range of 10 µm so that a line-pair covering 25 µm is being resolved onto $2 * \sqrt{2}$ pixels, in accordance with the Kell-factor (Kell et al., 1940). A single black & white film image will be translated into a file of size 529 MB, if each pixel has 8 bits (color at 1.56 GB). At 12 bits per pixel, this grows by a factor of 1.5.

1.3 Practical Values for the Size of Pixels

Actual scanning is often with larger pixels, say at 15µm or 25µm or some multiple of a particular scanner's "native" resolution. The reason is radiometry: film is inherently a binary document with exposed and developed grain elements being black in a negative, and inter-grain space being white. If pixels were small enough, all one would need is a 1-bit number. A scanner produces for each pixel a 12-bit number and thus more than 4,000 different gray levels for each pixel, irrespective of its size. What is the proper 12-bit pixel size for a 1-bit source document? The geometric contents of the film seem to get preserved on pixels that are larger than a strict lp/mm-rule would suggest. The transition from the analog (1-bit) film-domain into the multi-bit digital domain is not yet well explored.

1.4 Edge Response as a Measure of Geometric Resolution

The modern measurement of geometric resolution is the "edge response". A high-contrast "edge" is imaged on film and scanned. The transition from bright to dark defines the edge "sharpness" and is considered to be a measure of geometric resolution. Figures 1 and 2 illustrate the concept with an example taken from Blonski et al. (2002). The theory is explained by Ryan (2002). The edge in an image (Figure 1, left) is defined as a 3D shape (right). A 2D edge signal is obtained (Fig. 2 left). A Line-Spread-Function (LSF) is obtained as the first derivative of the edge signal, and produces a Gaussian-type curve, as shown in Figure 2 (right). Its full width at 50% of maximum amplitude (Full Width at Half Maximum, FWHM) is the resolution measure. Of course as the contrast gets reduced or radiometric noise increases, the geometric resolution will suffer.

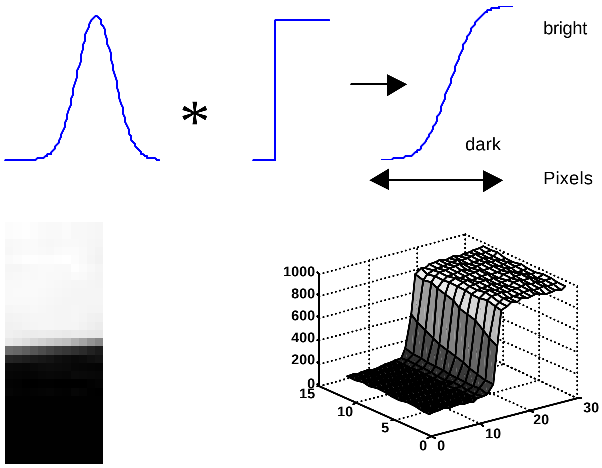

Figure 1: A sensor system's PSF (point spread function) is convolved with a perfect edge to produce a real edge function (above, from Ryan, 2002). A real edge image (left) represents a 3D shape (right), from Blonski et al. (2002)

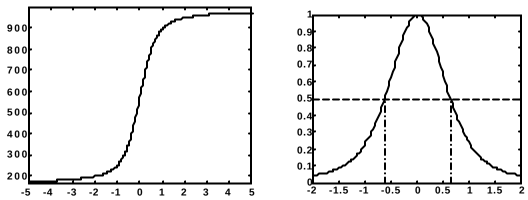

Figure 2: The 2D version of the 3D edge function is shown to the left, and is obtained from Fig. 1 (right). The first derivative of this real edge function creates a line spread function LSF. The width of the LSF at 50% of the amplitude is a measure of the geometric resolution (from Blonski, 2002). The horizontal dimensions are in pixels.

1.5 The Digital Image Replacing the Film Image

The film image results in an array of 11,500 by 11,500 pixels if scanned with pixels at 20µm, or a 15,000 by 15,000 pixel array results from a pixel size of 15µm. However, each of these pixels can be presented with 12 bits whereas the film in fact may not contain more than 6 bits per pixel at pixel sizes of 15 or 20µm. In film scanning, this may not be a major issue since scanners do produce sufficient geometric resolution to scan at very small pixel sizes. In addition, digital storage has become so inexpensive that it is not important whether an array of 15,000 x 15,000 pixels or more is representing a film image. It is not important to understand whether these pixel arrays are redundant for the information they contain. As we will show, this consideration is different when making the transition to the digital camera.

2. OBTAINING COLOR FROM A SINGLE AREA CCD ARRAY: THE BAYER APPROACH

2.1 Color and Geometric Resolution

Digital color cameras have become a commodity, both at the consumer level as well as in the professional arena. Color is obtained by special color CCD arrays in which each pixel has a filter and can thus record only light from that color segment of the spectrum for which the filter is designed. Figure 3 illustrates the typical RGGB-arrangement that is denoted as "Bayer-pattern" (Bayer, 1976; Adams, 1997). Figure 4 is an example from the RGGB- filter pattern.

Of interest is the accuracy of the color and the effect on the geometric resolution of a camera using this coloration approach. As one can easily see in Figure 4, the two green images differ. Filters and CCD-elements may not always be perfectly aligned, thus compromising the "color measurement".

R	G	R	G	R
G	B	G	B	G
R	G	R	G	R
G	B	G	B	G
R	G	R	G	R

Figure 3: The Bayer-pattern with its RGGB-colors on a 2 x 2 pixel array to obtain color measurements with a single area array CCD.

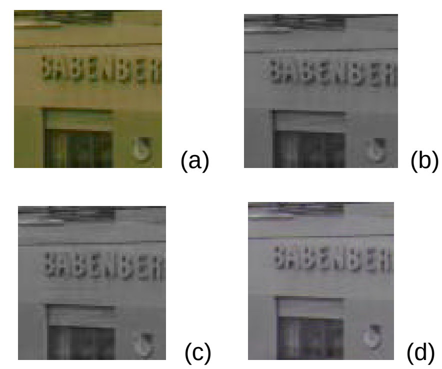

Figure 4: Example of a color image using the Bayer-pattern. (a) Color. (b) Green channel 1 @ mean gray value 106; (c) Green channel 2 @ mean gray value 111; (d) False color using the three channels green1, green2, 0.5*(green 1 +green2).

Each camera manufacturer uses a proprietary "demosaicking" algorithm to accomplish the coloration. The resulting image is produced as if at each of the native pixel locations one had observed an independent set of red-green-blue triplets.

The geometric resolution of a color-CCD producing 3K x 2K color pixels differs from that obtained with a 3K x 2K panchromatic CCD The differences in geometric resolution are not well understood. In each color band, the resolution is but a fraction of the panchromatic arrangement since there are only 1,500 x 1,000 pixels in red and blue, and 2 sets of green images at 1,500 x 1,000 each. The "edge response" as a measure of geometric resolution treats the resulting color image as if it were a panchromatic image. The resolution is compromised somewhat, with values that are in need of investigation.

2.2 Aerial Cameras

Initial product offerings with color CCDs based on the Bayer-pattern are by Emerge Inc. (Emerge, 2002) and by Enerquest Inc. (Enerquest, 2002), using Kodak 4K x 4K CCD chips. The systems are based on commercially available off-the-shelf components. The proprietary value of these vendors is in the systems configuration of standard components and calibration.

When examined with respect to conventional aerial film cameras, these digital solutions offer a field-of-view at less than 4K x 4K pixels. This is less than traditional aerial cameras and results in an increased number of flight lines, in limitations of the stereo arrangement and in a much greater number of images to be triangulated. Color is of a reduced quality since the filter-CCD registration suffers from imperfections. Yet, for corridor-type projects along roads or railroad tracks, or in support of laser scanner operations, these systems may find their applications. After all, they are being offered at a cost that is less than that for a new aerial film camera.

3. OBTAINING COLOR FROM MULTIPLE AREA CCD ARRAYS

3.1 The Approach

Accurate color at full geometric resolution can be obtained if a panchromatic area array CCD is combined with a color filter. For each color, a separate CCD-filter combination needs to be used. The resulting color image is a superimposition of three separately collected component images in red, green and blue. Often a 4^{th} component is collected in IR.

3.2 Aerial Cameras

An early solution using 4 CCD-filter combinations to include infrared was by Positive Systems Inc. (Positive Systems, 2001) and its ADAR-series, for example the ADAR5500. Four digital panchromatic cameras were being configured side-by-side at a performance in function of Kodak's offering. The solution is no longer being offered as a product, but is being employed by companies producing color ortho-photos.

The camera format issues are the same as in the Emerge/ Enerquest-approach, and therefore the product was not able to carve a niche in the photogrammetric market. But the color measurement is more accurate, and some remote sensing applications were found for this technology.

4. THE PUSH BROOM APPROACH USING LINEAR ARRAY CCDS: DLR AND LEICA-GEOSYSTEMS

4.1 Remote Sensing

Remote sensing applications have long employed scanning in the cross track direction and assembling of an image from individually collected scan lines (Remote Sensing Tutorial, 2002). Of interest is and was the creation of a single image strip assembled from many scan lines, but associating with each scan line multiple spectral channels. From aircraft this evolved into hyper-spectral imaging with several hundred color channels, but without any concern for geometric accuracy. From space, this has become the preferred imaging approach in terrestrial observations. The stability of an orbital path is sufficiently high so that the resulting image has a high geometric accuracy. A pixel may cover 2m or more.

4.2 Simultaneous Collection of Multiple Image Lines

Derenyi (1970) was the first to point out that one could collect three or more scan lines simultaneously and thereby obtain a strong geometric solution for the flight path. He illustrated that one could in effect reconstruct the flight path by considering each triplet of scan lines as if it were cut from a frame camera image. This would produce an aerial triangulation with as many central perspective camera images as there are scan lines. Goetz (1980) expanded on this idea proposing a stereo satellite mission called Stereosat. These initiatives did not make it beyond study phases.

The German Aerospace Center DLR built a series of systems that employed the same approach, however in an implementation originally proposed by Hofmann and described for example by Hofmann and Mueller (1988). Cameras producing multiple image lines looking forward, downward and backward were built for the MOMS terrestrial satellite camera (MOMS, 1996) for Mars exploration (Mars, 1996). The system is denoted as High Resolution Stereo Camera HRSC and is discussed by Neukum et al. (2001). This camera is being flown by ISTAR in France under an agreement with DLR.

Finally, a product development was undertaken by Leica Geosystems, also under an agreement with DLR, resulting in their ADS40 camera (Leica, 2002, Sandau et al, 2000). Figure 5 shows that an aircraft flying a flight line will produce multiple image strips, each composed by an assembly of collected image lines. The multiplicity of the image strips is for geometric purposes to take advantage of the forward-downward-backward geometry described by Derenyi (1970) and Konecny (1970), as well as to create multi-spectral images, using a CCD-row per color.

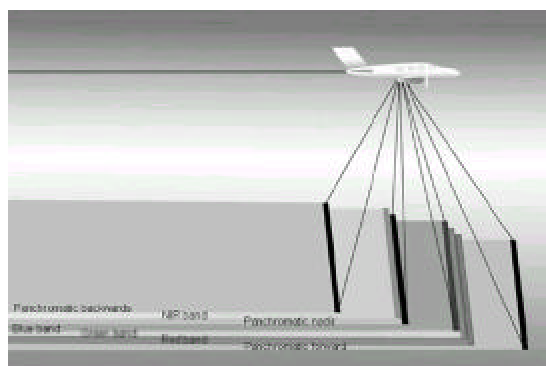

Figure 5: Operation of the ADS40 camera by Leica Geosystems as described on the company's web site.

In the transition to a commercial product, Leica-Geosystems implemented a number of interesting ideas. For example, the geometric resolution across the track is increased by the use of two CCD-lines that overlap and are displaced with respect to one another by half a pixel in the cross track direction. The vendor then claims a geometric resolution of 24,000 pixels cross track using 2 CCDs of length 12,000 each.

4.3 Relating the ADS40 to a Film Camera

The novel camera produces a great number of pixels very rapidly and across a wide swath at 12,000 (or 24,000) pixels per image line, 7 lines at a time. In that respect the solution is superior to the small format CCD-cameras mentioned earlier.

However, the geometric accuracy of the resulting images depends entirely on the ability of tracking the exterior orientation of the sensor. The “triangulation” according to the principle first proposed by Derenyi (1970) is not strong enough to indeed solve for the flight path with sufficient accuracy and to respond to rapid changes of the sensor’s exterior orientation. “Tracking” is thus needed to achieve a sort of “dead-reckoning” solution. The measurement of the exterior orientation of the sensor is by means of GPS and INS.

It is typical for line-based sensors that rapid changes of the sensor orientation may result in object details to disappear. The system reads out an image line when the camera pointed in one instant at one location. The next readout may occur of the camera pointing a little later to another surface point. The surface detail in between the two positions may disappear.

The velocity of flight limits the dwell time of the CCD element on a specific surface location. The lower the sensor flies, the shorter is the available dwell time and the poorer is the radiometry. Therefore the linear array approach may have inherent limits on the smallest pixel sizes on the ground. At 7 cm pixels, the dwell time would at 1 msec. In film cameras, such a limitation is overcome by longer exposure times in combination with a forward-motion-compensation FMC. This is not available for a linear array sensor.

Finally, the images obtained from the sensor are not consistent with photogrammetric standards. This may be commented with a reference to a “nostalgic farewell to the frame photograph”, but it results in a serious sensor specificity of the image analysis workflow: all photogrammetric processing will need to be reinvented for this specific sensor.

The dead-reckoning need of the sensor contradicts the principle of a photogrammetric measurement sensor. The images themselves do not contain sufficient geometric information to reconstruct the sensor orientation and object geometry.

5. THE PUSH-BROOM APPROACH WITH AREA CCD ARRAYS: THE MAYR-TEUCHERT PATENT

5.1 Principle

When considering the basic idea of imaging in multiple, simultaneously collected strips, one may wonder what other triple strip approaches one could use? Teuchert and Mayr (2000) patented the idea of replacing the individual CCD-line by a set of small area array CCDs. A camera cone will not hold three CCD lines, but will hold instead a set of area arrays, looking forward, downward and backward. Each group of arrays is assembled to produce one image “strip” and three strips get built in a flight line. But since the arrays cannot abut seamlessly, there will be holes in the three resulting image “strips”. These holes get filled by means of appropriately arranging the multiple area CCD arrays on the focal plane, and exploiting the forward motion of the airplane.

5.2 Realization

There have been no reports that the proposed camera system has been built. There are conceptual advantages in using area arrays over linear arrays, considering the need for long dwell times and for the availability of FMC. An issue would certainly be the cost of goods: is it going to be competitive vis-à-vis other technologies? And is the resulting set of images sufficiently similar to current inputs into existing workflows?

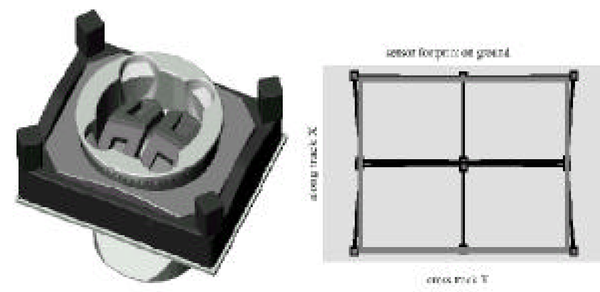

Figure 6: The DMC by Z/I Inc consists of 4 independent camera cones to build one large image, and additionally 4 cones to add color in red, green, blue and infrared. Each of the color images is at a fraction of the resolution of the panchromatic images. From the 4 individual images a “virtual image” is built (Source: Z/I inc., 2002).

6. MULTIPLE OPTICAL CONES FOR HIGH RESOLUTION PANCHROMATIC AND LOWER RESOLUTION COLOR IMAGING: Z/I INC.

6.1 Coping with Area Array CCDs with Insufficient Size

The “perfect” replacement for the film camera would be based on a very large area array sensor. There would need to be a sufficient number of pixels to be equal or better than precision scanned aerial film. A 20µm pixel size produces 11.5K by 11.5K pixels, and that would be the desired array. Such a CCD-array is not being produced. The largest CCD-array to be presented is by BAE of New York with 9k x 9k, used for aerial reconnaissance (Gorin et al., 2002). To get very large arrays, one needs to approach this issue in some other form. Z/I Inc. builds its photogrammetric digital camera using the idea of a “virtual image” composed from 4 smaller component images (Hinz et al., 2000). Large area CCD arrays are being built for mammography at a format of 7K x 4K pixels. Four of these could be assembled into a system with a little less than 14K x 8K pixels in black & white. Figure 6 is from the Z/I-web site.

Multiple images can be made to fit together appropriately into a large image if their geometry is predictable. This is being achieved if the exposures are taken at the exact same moment in time so that the exterior orientation of the 4 camera cones is identical. While in theory the virtual image has 4 different perspective centers, this can be neglected since the distance between the individual camera cones is a mere few cms.

The color images are exposed onto an array of 3,000 x 2,000 pixels for each color component. The 3K color values in image row must color 14K output pixels. Therefore their geometry is not as restricted as that of the panchromatic images.

6.2 Comments

This solution employs multiple area CCD arrays and camera cones, with one CCD array per camera. Conceptually each camera produces its own central perspective and has its own coordinate system, much as if the pre-WWII-concept of multiple cameras had been resurrected. These pre-WWII-multiple cameras were used to overcome limitations in the field of view of the then available narrow angle optical systems. If one were to employ the solution in this manner, it would not dovetail well with the current photogrammetric workflow.

For that reason, Z/I offers the "virtual large image". However, there is no master coordinate system available for the 4 component images. Instead, each component has its own coordinate system. If the component images have different exterior orientations then they no longer are defined in the same coordinate system. Such differences may occur if the shutters malfunction only imperceptibly. These differences will affect the overlap between the four image parts where they abut. One will note that something is incorrect, but there is insufficient information in the images themselves to model and correct the error. The image areas at the outside corners of the resulting virtual image may have a weak geometry.

One may argue that the camera "extrapolates" pixel coordinates at the corners of the resulting image. This extrapolation is in contradiction with the requirement for a photogrammetric camera to serve as a measuring tool.

7. FILM VERSUS CCDS: A COMPARISON

7.1 Radiometry

The above discussion does not present a good argument to switch from a film camera to a digital sensor. Proposed solutions suffer from poor fields-of-view and small formats, from weak geometry, and ultimately also from high cost. However, a closer look at digital camera images reveals that the radiometric performance of digital cameras can be superior.

Figure 7: Rollei 6006 image using Ilford FP4 film scanned at 5µm pixels. Taken at 1:1.000 with a 50mm lens from a distance of 50 m. Each pixel is 7mm in object space.

Figures 7 and 8 compare a digital image with a scanned film image, with pixel size about equal in object space. The graininess of the film source produces a far inferior image to the 12- or 14-bit digital product of the same object.

7.2 How Many Pixels?

Spoiled by near limitless storage capacities, film scans have become customary at 10 or 15 µm per pixel, with little justification for this pixel size. However, when a CCD array needs to get used, technology presents significant limits. Therefore it is useful to understand how many 12-bit pixels will represent the same information as a 23cm x 23cm film image. Is it 12,000 x 12,000 (Leica Geosystems Inc.) or 14,000 x 8,000 (Z/I Inc.)? Or is it 8,000 x 8,000? The question is open for analysis and review. As Perko & Gruber (2002) indicate, a 12-bit CCD pixel is certainly superior to a 15µm scanned film pixel.

Figure 8: Same as Fig. 7, but with a digital camera using a Dalsa CCD chip with 6 Mega-pixels. On the object, each pixel represents the same 7mm as in Figure 7.

8. IN CONCLUSION: SPECIFYING THE DIGITAL AERIAL CAMERA TO REPLACE THE FILM CAMERA

The future of photogrammetry may result in a confusing variety of non-standard aerial camera systems, each to be associated with a different workflow and in need of different analysis tools. This is at least the impression one has to get as one reviews the variety of ideas and products currently proposed. None of the proposed solutions promises to replace the conventional aerial film camera.

- Either the productivity of the new cameras is too low to compete,
- or the cost of the new camera contrasts with an economic justification vis-à-vis the traditional film camera,
- or the workflow with a new camera conflicts with current traditions in the field.

We believe that a novel and successful digital aerial camera will have to create a digital image much as if it had been obtained by a film camera and then scanned, thus offering a field-of-view and a geometric resolution commensurate with a traditional aerial camera. But in addition there are other important factors that should accelerate the acceptance of such a novel aerial camera. We believe that a successful digital aerial camera will have to:

- be a photogrammetric measuring tool and thus produce geometrically predictable imagery in a rigid coordinate frame, much as traditional aerial photography does;
- cost significantly less than a new film camera, perhaps by a factor of 2;
- offer better radiometry;
- produce images at a sustained rate of 0.5 seconds per image or less;
- be smaller and lighter than conventional aerial cameras, perhaps by a factor of 4, and thus be easier to handle;

- support the aerial operation by providing on-line image based navigation, verification and quality control, and by reducing the need for a second highly trained specialist during survey flights;
- be easily calibrated in a self-calibration approach;
- be financially advantageous over the operation by an already existing film camera, even if that camera is entirely written off, simply by the savings in cost of film and cost of scanning, over a period of 2 years or less;
- be modular so that it can be configured to specific needs and that its performance can be upgraded as technology advances.

The combination of small pixel sizes and high radiometric sensitivity at 12 or 14 bits per pixel in each color channel is unique to digital sensors and needs to be properly juxtaposed to an analog film image which has less and less radiometric resolution as the scanned pixels become smaller. In the extreme case, a very small pixel from a scanned film image presents only binary information, whereas the individual CCD-pixel is still a 12 to 14 bit measurement of radiometry. We believe that an aerial camera can be built and can be brought to market to satisfy the requirements enumerated above.

This will match with the "traditional" softcopy photogrammetric workflow with existing software and methods from a variety of photogrammetric software vendors. We believe that the digital camera revolution will begin when such a camera becomes available.

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