IS THERE AN IDEAL DIGITAL AERIAL CAMERA?

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ABSTRACT :

The IGN digital camera project was set up in the early 90's and the first research surveys were carried out in 1996. The digital camera was first used in production in 2000 when the DMC and ADS40 systems appeared on the market at the beginning of the 21st century. Since then, two medium format systems (Applanix DSS322 and DiMAC system) and a third large-format system (Vexcel UltraCamD) appeared on the surveying market. Today, IGN's system could appear very underperforming in terms of possible swaths and frame rates compared with the ones offered by large format cameras ; and parts of our electronics have become obsolete. This is the reason why we recently reanalyzed the needs of IGN in term of digital imagery and confronted them to the main characteristics and capabilities of the different existing commercial systems. Considering that Bayer acquisition without a coupled panchromatic acquisition does not allow an image reconstruction of good quality and considering that an acquisition system based on CCD area sensors must be equipped with a Forward Motion Compensation (FMC) able to compensate dozens of pixels, we only focused on the three large-format systems that are : Intergraph's DMC, Vexcel's UltracamD, and Leica Geosystems' ADS40. Each of these three systems has its pros and cons and no one seems to bring an answer to all our needs.

1. THE IGN DIGITAL WORKFLOW

1.1. Historical development

IGN, thanks to its own made camera system, began to adapt its production lines to digital imagery in 1998. Last year, no more silver halide photographs were acquired for IGN production units. Since the first digital research survey over the town of Amiens ten years ago, our camera system's specifications were constantly upgraded in order to bring answers to IGN users' needs (Thom and Souchon, 1999), (Thom and Souchon, 2001).

Black and white surveys were quickly swept away by color surveys. Color acquisition by the mean of color Bayer (Bayer, 1976) sensors put the stress on the limits of such a technology and brought the laboratory to work on the multi-camera heads concept. 6 Megapixels CCD sensors, considered as large sensors in 1995 were replaced when 16 Megapixels CCD sensors became available. No doubt that these 16 Megapixels sensors will know the same fate with new incoming sensors of more than 30 Megapixels. Near infrared channel is today systematically acquired thanks to a fourth camera head to satisfy forest and water agencies. PC Hardware progress, in term of disks storage capacity for instance, will be deliberately forgotten in this paper.

1.2. The actual state-of-the-art

The camera head properties are listed in Table1. Concerning the system itself, specifications evolutions are now limited to the tests of new geometric configurations of the different camera heads to improve the two main digital workflows of IGN today.

On the one hand, the orthophography production lines that deal with the whole French territories every five years. The ground sample distance acquired for this application in the four color channels improves year after year, from 83 cm in 2003 to 68 cm in 2005 with some tests at 50 cm. The flight costs and durations are directly linked to this GSD and of course a special configuration with the use of pan-sharpening have been tested to compensate our 4096 pixels swath (Fig. 1).

CCD array size	4096 x 4096 pixels, Kodak KAF-16801LE
Swath	4096 “4-channels”design – 6980 “panchro+XS” design with 2.7 pansharpening ratio
Full well capacity of each pixel	55000 e^-
Dynamic range	2000-3000 grey levels
Radiometric resolution	12 bits / channel
Frame rate	1 image / 3.2 seconds
Minimum stereo GSD	19 cm (60% stereo overlap, 100 m/s plane speed)
Storage capacity	Unlimited (hot removable hard disks)
Electronic motion compensation	Yes : Time Delayed Integration (½ pixel accuracy)
Focal lengths	28, 60 and 100 mm Rollei Digitar (Application dependent)
Exposure time	3 ms minimum. No upper bound.
Synchronization accuracy	< 10 µs

Tab.1. Main characteristics of IGN’s digital camera

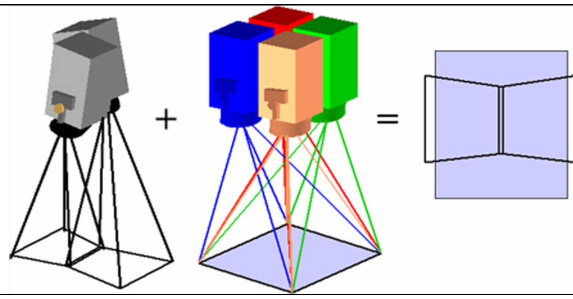

Fig. 1a : the general view of the “panchro+XS” design of IGN, coupling high resolution (40 cm) panchromatic images (with a butterfly camera equipped with 100 mm focal length) and lower resolution (68 cm) colour images (4 camera heads with 60 mm focal length). The resulting color images is 6920x3930 pixels.

Fig. 1b : extract of the initial GSD 68cm image re-sampled to 40 cm (bicubic re-sampling)

Fig. 1c : the same area resulting of the fusion between GSD 40 cm panchromatic and GSD 68 cm color image

On the other hand, for 3D city models reconstructions, our system was adapted to allow the acquisition along the same the flight strip of a four channels orthophotography at a 15-20 cm GSD and of façades features thanks to two black and white camera heads in forward-backward or left-right configurations.

1.3. And what about the future ?

Considering that parts of our electronics have become obsolete and considering that our system could be improved in terms of possible swaths and frame rates compared with the ones generally offered by large format cameras, a study was carried out at IGN in order to find a technical solution to face up to the future digital needs. IGN users' needs in term of digital imagery were recently reanalyzed. The minimum stereoscopic GSD is sensed at 10-15 cm for 3D city models surveys and at 40-50 cm for whole territory orthophotography surveys. The swath must be of course as large as possible but the field of view must take into account an orthoimage production requirement with a constraint on the maximal size of occluded areas : a 1/6 hidden to height ratio seems to be realistic. A pan-sharpening process with a reasonable ratio (actually 2.7 black and white pixels colored by one color pixel) appears to be conceivable by users. The camera system must be operational as well in winter conditions as in classical summer conditions to avoid leaves in the trees. A consequence of this is that long exposure times must be reachable and consequently an accurate forward motion compensation of dozens of pixels. Some others unavoidable specifications are : an anti-blooming protection, a wide range of focal length for the lenses, the opportunity to change easily the spectral bandwidths of the filters for some specific research surveys, in other words a modularity. A Bayer color acquisition can be foreseen at the only condition it is coupled with a panchromatic acquisition to allow a better image reconstruction. On the other hand, a near infrared channel acquisition with a Bayer sensor used in false color configuration is totally incompatible with the need of a good geometric quality. In this configuration, a specific filter allows the near infrared radiations to pass instead of the blue ones, and then to be acquired in the same focal plane than the red and green channels on the color CCD.

2. THE PROS AND CONS OF DIFFERENT CAMERA SYSTEMS IN FRONT OF FUTURE IGN NEEDS

Among the wide choice of digital camera systems, we focused on two medium format systems (Applanix DSS322 and DiMAC systems) and the three main large format systems that are Leica Geosystems' ADS40 (Sandau et al. 2000) using linear technology, and Intergraph's DMC (Hinz et al., 2000) and Vexcel's UltraCamD (Leberl and Gruber, 2003) using mosaics of large array sensors.

2.1. Applanix DSS322 and DiMAC

These two systems offer the same disadvantage : the use of camera head equipped with color Bayer sensors only. It has many consequences on the image quality :

- The color reconstruction without the help of a synchronous black and white acquisition brings to several color artifacts particularly on linear structures (Fig. 2) that led us in 1999 to study multi-channel acquisition
- The near infrared channel focal plane is not localized at the same place as the visible ones. Consequently, the near infrared channel will be blurred if the RVB channels are well focused…
- Most of the lenses induce chromatic aberration and distortion in the different channels. For instance the blue channel distortion will be several pixels different from the red channel distortion in the limit of the field of view. This leads to colored staggering in the images (Fig. 3) if no calibration measurements and color reconstructions are done.

In the absence of forward motion compensation, the Applanix DSS322 is automatically rejected. Unfortunately the "true FMC" of the DiMAC system doesn't allow more than 60 µm (i.e. less than 7 pixels) compensation : sufficient for summer flight conditions but not for an acquisition of good radiometric quality in winter.

2.2. Leica Geosystems's ADS40

A big advantage of the ADS40 is a swath of 12000 pixels in the four color channels without any needs of pan-sharpening. This advantage coupled with a specific optical design for the lens and the use of a trichroïd splitters brings to a very good image quality when many conditions are respected like good weather, accurate Inertial Measurement Units and a plane flying at a reasonable speed.

At IGN, there is of course an historical preference for array technology, but people seems to be more worried about the geometric accuracy than about the radiometric quality of images acquired with systems based on linear technology. On the one hand, progress have undeniably be done in geometric reconstruction, perhaps thanks to more accurate IMUs. On the other hand, the interdependence between the plane speed and the exposure time does not allow users to fly at any speed and in any weather conditions. Another disadvantage of this system is its line rate that brings to a minimum GSD of 12 cm with a plane speed of 100 m/s. As consumers always want to see more and more details in images it will certainly a limit in a near future.

More specific disadvantages could be no color information in the façades (a bad point for 3D city models), separate spectral bandwidths without any overlapping that are perhaps useful for remote sensing but not for realistic colorimetric content and no possibility offered for Bidirectional Reflectance Distribution Function (BRDF) measurement.

	
Fig. 2 : samples of color artifacts due to color reconstruction of an image acquire with the Bayer CCD of Applanix DSS322	Fig. 3 : samples of colored staggering in the images of Applanix DSS322 due to different distortion parameters between the channels

2.3. Intergraph's DMC

This large format system is based on the array sensor technology. It's composed of two sub-systems :

- The black and white sub-system : four camera heads equipped with 7168x4096 pixels (12 µm square pixels) array sensors and lenses specially designed with a 120 mm focal length. These four cameras are tilted in order to acquiring a "butterfly" black and white image of 13824x7680 pixels.
- The color sub-system : four camera heads equipped with 3072x2048 pixels (12 µm square pixels) array sensors and lenses specially designed with a 25 mm focal length. These four cameras acquire the red, green, blue and near infrared channels in a vertical configuration.

The final image is obtained by coloring the "butterfly" image with the color information with a pan-sharpening process. The result is the largest color image actually reachable on the market. Two other advantages of this system are a frame rate that allows a 6.5 cm minimum stereoscopic GSD and a specific optical design that induces a very good image quality in the raw images. Unfortunately this last advantage is annihilated by a pan-sharpening ratio of 27 (27 black and white pixels colored by one color pixel) that leads to strange phenomena like color artifacts, false color registration and some ghost appearing in the neighboring of color objects (Fig. 4). Bigger is the GSD, the more uncomfortable is the vision of images acquired with the DMC : of course the use of 6.5 cm GSD images brings customers to reduce images scale on the screen and in the same time to rub out the effects of pan-sharpening ; but for a middle-scale use at IGN with a 50 cm GSD, color acquisition will be made with a 2.5 m GSD like with satellites.

The "butterfly" acquisition has a consequence : the middle of the final image is the contribution of four images corners that are for optical reasons more blurred that the centers of the raw images.

2.4. Vexcel's UltraCamD

This large format system has been thought to propose an alternative to the DMC. It's also based on two sub-systems :

- The black and white sub-system : four vertical camera heads equipped with several 4008x2672 pixels (9 µm square pixels) and off-the-shelf Rollei Digitar lenses with a 100 mm focal length. These four cameras acquired a mosaic of nine arrays : the final image is 7500x11500 pixels large. The master cone is equipped with for CCD arrays placed in the corners of its field of view. The gap between the four arrays of the master cone are filled by the three other panchromatic cones. All panchromatic cones have the same field of view thanks to the concept of a "syntopic" imaging (Fig. 5) : the four black and white camera heads are arranged linearly along the flight direction and aperture of the shutters are delayed.
- The color sub-system : four camera heads equipped with the same 4008x2672 pixels array sensors and off-the-shelf Rollei Digitar lenses with a 28 mm focal length. These four cameras acquire the red, green, blue and near infrared channels in a vertical configuration.

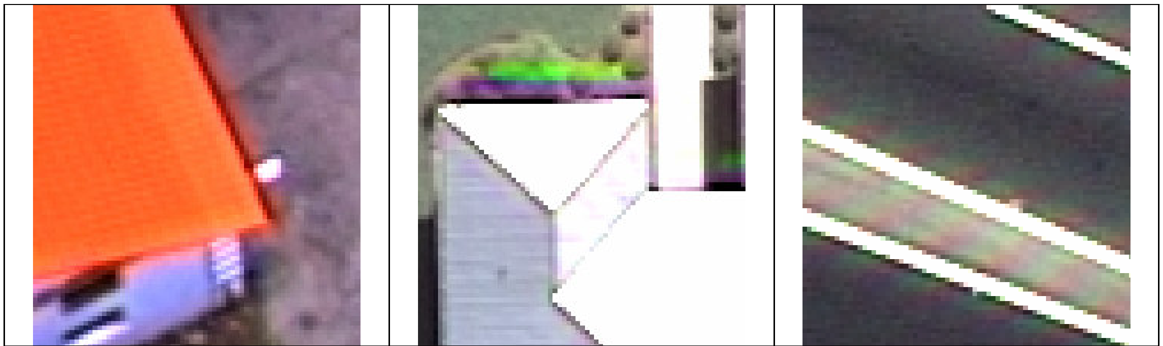

Fig. 4a. Classical bad color delimitation : here a roof that spreads on the street. Fig. 4b. Sample of a “strange phenomenon” certainly due to the color reconstruction by pan-sharpening : magenta and green echoes on the edge of bright areas. Fig. 4c. typical “ghost” on dark areas like streets : iridizing streaked by white lines

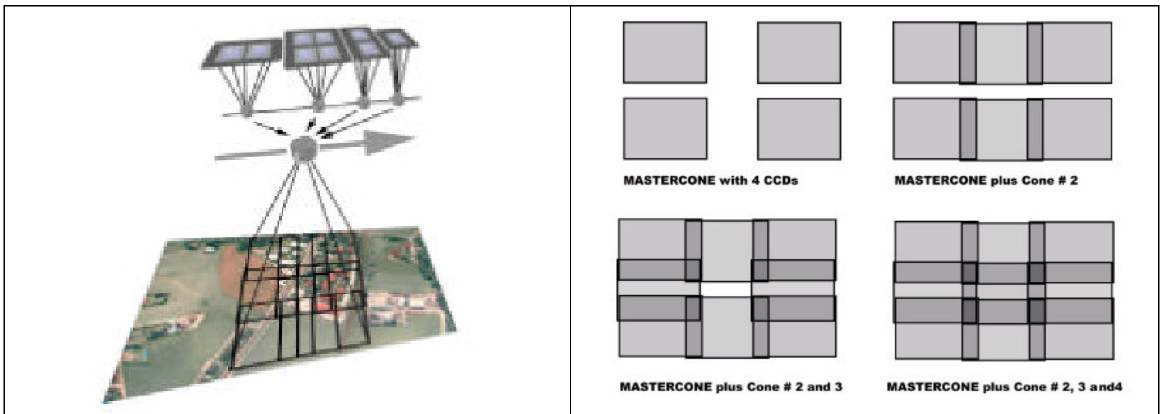

Fig.5. the concept of “syntopic” imaging of Vexcel’s UltraCamD (*Source: Vexcel Imaging*). On the right, contribution of each “cone” to the final mosaic.

Fig. 6. Consequences of the use of off-the-shelf lenses with the UCD on the geometric quality in the corners of images. From left to right : lower-left corner (GSD : 5cm), upper-left (GSD : 5cm), upper-left (GSD : 20cm), upper-right (GSD: 20cm)

Besides a minimum GSD of 2.5 cm that is the smallest on the market, the two major differences with the DMC are the vertical axis of all the camera heads that is an advantage ; and an economical alternative with the choice of off-the-shelf lenses that is unfortunately a big disadvantage. Our own experimentations with Rollei Digitar 28 mm demonstrated that it’s very difficult :

1. to model accurately and in a dense way, the distortion in the different channels to reach a good superimposition of the color channels everywhere in the image
2. to reduce the important field curvature to avoid a difference of focusing between the middle and the corners of the image.

The result is a color image of average geometric quality that will be used to color a more resolved black and white image. This is processed with a pan-sharpening ratio of 17 (instead of the 27 of DMC) and has major consequences on the image quality in the corners of the images (Fig. 6).

This phenomenon is intensified by another technical specification of the UCD. The image circle of the Rollei

Digitar 100 mm initially given with a diameter of 75 mm has recently be enlarged to 100 mm that is still slightly short for a black and white mosaic whose dimensions are 103.5 mm by 67.5 mm (that leads to a diameter of 123.5 mm).

The three large format camera systems have two common disadvantages :

- Too large field of view cross track (55° for UCD, 62° for ADS40, and 69.3° for DMC) that leads to numerous occluded areas (Fig. 7). If we retain a 1/6 hidden to height ratio, the respective 11500, 12000 and 13824 pixels swaths become 3550, 3230 and 3327 pixels swaths. In front of this, our "panchro+XS" configuration with a good choice of focal length, possible due to our modularity, is not underperforming at all.
- No modularity in terms of choice of focal lengths of the lenses and of bandwidths of the color filters.

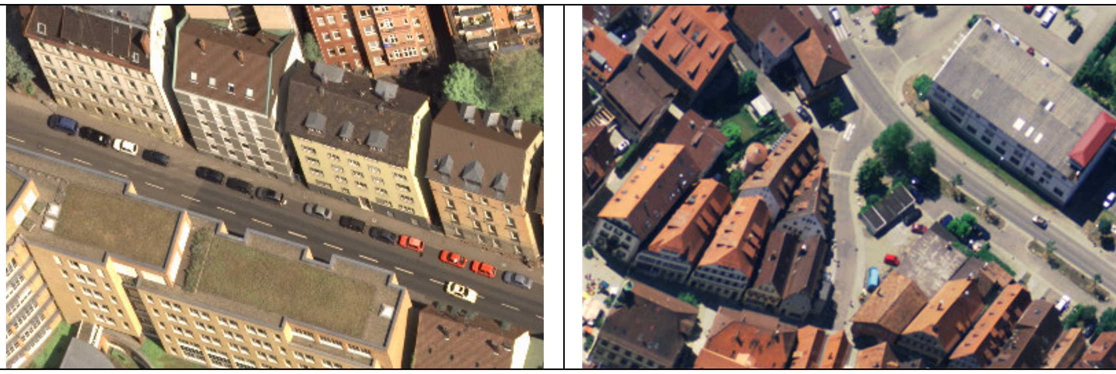

Fig. 7. Field of view cross track of 69°3 for DMC on the left and 62° for ADS40 on the right leads to numerous occluded areas on the borders of the images.

3. CONCLUSION

Is it possible to put together the advantages of all the systems ? The ideal system would then be a system that have the price of Applanix DSS322, with a minimum GSD under the 10 cm limit like UCD and DMC, with no recourse to pan-sharpening (linear technology like ADS40) or with a recourse to it with ratio comparable to the one already tested at IGN and that doesn't bring any visible color artifact. An ideal system with the optical quality of the DMC and ADS40 but using more affordable off-the-shelf lenses like UCD, with the array technology to have exposure time independent from the plane speed, and a system with an accurate forward motion compensation to have GSD independent from exposure time. Of course this ideal system should offer the same modularity as actual IGN system. This system should have a final swath, after pan-sharpening process, of about 13000 pixels. No doubt that the recent progress in term of large CCD array sensors will give us the material to approach this ideal system…

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