INNOVATING THE PHOTOGRAMMETRIC WORKFLOW[1]

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ABSTRACT

While initially the introduction of the digital large format aerial cameras seems nothing more than a replacement of film and film scanners, the effect is more fundamental. "Softcopy photogrammetry" is no longer a simple digital copy of film photogrammetry, but new procedures and new products are becoming feasible. Photogrammetry enters into the world of "augmented" and "virtual reality", with a transition from the 2-D map products to 3D models of the real world.

1. INTRODUCTION

1.1 Digital Aerial Cameras

The transition from the traditional large format photogrammetric film camera to the novel digital camera finally makes it possible to operate a fully digital workflow, from flight planning to the orthophoto product. While this innovation had been announced in 2000 at the Congress of the ISPRS in Amsterdam, actual introduction was delayed. As seen in Table 1, the number of digital cameras put into action started out hesitantly. Perhaps technology to process the large data sets created in a photogrammetric survey flight had to evolve a little further, so that 2000 was too early. Clearly, technology has made another leap by 2005, and the terabytes of image data are no longer insurmountable mountains of data. As we can see from Table 1, the rate of accepting digital data and cameras is now accelerating. By mid-2005, 77 units have been put in to use.

	Leica ADS40	**Intergraph DMC**	**Vexcel UltraCam-D**	**Annual**	**Accrual**
2000	Announced	Announced		0	0
2001	1			1	1
2002	5			5	6
2003	7	3	Announced	10	16
2004	10	11	13	34	50
2005 (Jan-May)	2	12	13	27	77
Sum, End of May 05	**25**	**26**	**26**	**77**	

Table 1:
Large Format Digital Aerial Cameras Sold. Sources: Written and oral presentations at the ISPRS Workshop on "Digital Aerial Cameras", Hannover (Germany), May 2005.

Of interest may also be the geographic distribution of these 77 cameras, as presented in Table 2. It suggests that there is simultaneous and global acceptance of the new technology, and North-America is by no means ahead of the other regions of the world.

[1] Slightly modified from "Novel Digital Photogrammetric Workflow", to appear at Proceedings of the Semana Geomatica, August 2005, Instituto Geografico Agustin Codazzi, Bogota, Colombia.

Asia	29%
Europe	35%
North America	35%
Africa	1%

Table 2:
Distribution of operating digital aerial large format cameras. Form an oral presentation by Dr. Cramer, University of Stuttgart, at an ISPRS Workshop in Hanover (Germany, May 2005).

1.2 "A Lightning Transition to a World without Film"

Towards the end of 2007 it may well be that the majority of all aerial photogrammetric imagery is digital and no longer recorded on film. At that time, perhaps 200 digital aerial cameras will be operating at high productivity, whereas film cameras will increasingly become the exotic technology.

One should note certain press announcements by AGFA and by Kodak. On the 20th of July 2005, Kodak issued a press release (Kodak, 2005) about laying off a third of their workforce because of the "lightning transition to a world without film" that is catching even the insiders by surprise. Quote from the Kodak website:

> *"The company now plans to increase the total employment reduction to a range of 22,500 to 25,000 positions, and to reduce its traditional manufacturing infrastructure to approximately $1 billion, compared with $2.9 billion in January 2004."*

Another noteworthy message concerns AGFA-Germany's insolvency (Forbes, 2005). How much longer will aerial film continue to be available for purchase?

Figure 1:
Sample image taken with Vexcel's UltraCam-D camera. Flight altitude was 330 meters to produce a ground sample distance of 3 cm. Area near Graz (Austria).

1.3 Digital Aerial Images from the UltraCam-D

Figure 1 presents a sample digital aerial image with a ground sample distance (GSD) or pixel size of 3 cm. The airplane flies about 7 cm per 1 millisecond, and thus moves 28 cm during the exposure time of 4 milliseconds (1/250 seconds). Figure 1 illustrates that no motion blur is visible, because the camera system compensates for motion electronically.

Figure 2 compares two images of the same area, and with the same GSD of 8 cm. The example shows the superiority of the digital image over the film image that is contaminated by the film grain noise.

2. THE PHOTOGRAMMETRIC TECHNOLOGY CONTINUUM

"Photogrammetry" goes back to the 19th century, with the word being coined by Dr. A. Meydenbauer in 1893. The evolution of the field went gradually over many decades, until the advent of the digital computer. Figure 3 attempts to show how the computer affected the field by three major inventions: the analytical plotter in 1958, the softcopy processing of scanned film imagery, and finally the digital aerial camera.

Figure 2:
Comparison between film and digital cameras imagery. Left: Film. Right: UltraCam-D Imagery. Two cameras were flown on one plane.

However, the analytical plotter did not affect the labor needed, both in quantity and in quality. Only very small functions could be automated, such as the recording of the data that went to the computer instead to a drafting machine. As a result, it took a long time for the invention to get accepted broadly, more than 20 years, from 1958 to 1980. Only in 1980 did the analytical plotter become the main photogrammetric tool. Today, it is being used along with upgraded analog plotters.

The introduction of the softcopy photogrammetric process also did not really affect the use and role of labor in photogrammetry. Essentially, softcopy procedures transferred the work from the analytical plotter to the Personal Computer PC. But the procedures were not changed. The only true effect of softcopy photogrammetry was the “re-incarnation” of the orthophoto, which became a simple product to make once the film image was scanned. First photogrammetric scanners appeared on the market in 1990, and this marked the start of softcopy photogrammetry and of the new orthophoto. Even now, in 2005, thus 15 years later, softcopy has still not taken over from the analytical plotter or the digitized analog plotter – simply because it could not really offer a serious change of the procedures used in photogrammetry, and thus offer a compelling economic advantage.

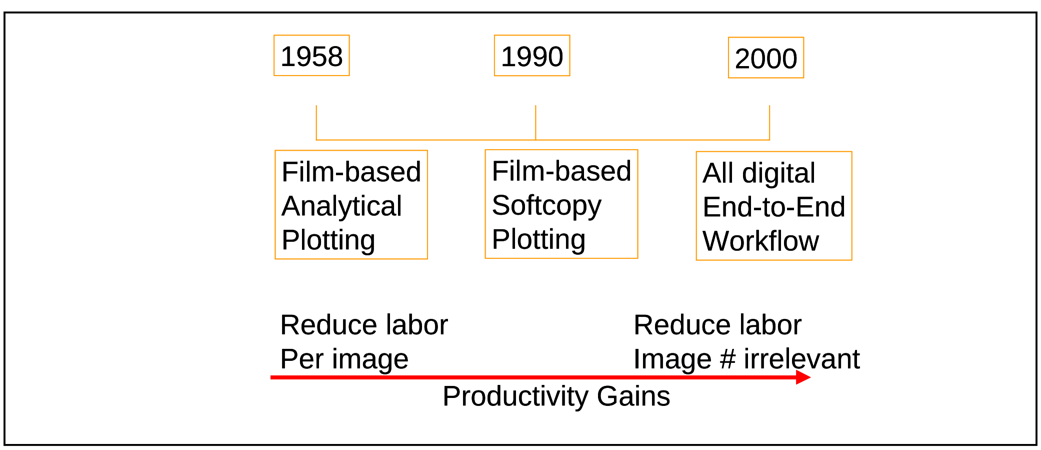


Figure 3:
The “photogrammetric technology continuum”

So the major global use of current softcopy photogrammetry systems is for the creation of ortho-photos. Some regions of the world have indeed abandoned the analytical and digitized analog instruments, such as in Spain or China; others still operate the softcopy systems only for ortho photos, such as in the USA. This documents that softcopy technology was not a major advance.

A total change is now occurring with the invention of the digital large format aerial camera. There is no film to operate with. Therefore the total abandonment of the analytical and digitized analog plotters is an unavoidable consequence. The transition is very rapid. Today is but 5 years from the initial announcement of the technology, and yet its victory is evident, global acceptance is a fact.

3. A TECHNOLOGY COMPETITION: PUSHBROOMING VERSUS FRAME-CAMERAS

3.1 What is a "Large Format" Aerial Camera, and what Makes it "Photogrammetric"?

"Large format" is the format used with film. Scanning film with pixels of 20 μm produces a pixel array of 11,000 x 11,000 pixels. "Large" is thus an image with a swath width at 11,000 pixels or so. Recent public tenders have demanded that aerial cameras have a swath width of at least 10,000 pixels to be competitive.

One might want to discus the proper pixel size for scanning aerial film. As demonstrated by Perko (2005), a pixel size of 20 μm amply captures the information contained in a film image.

Medium format cameras that have become somewhat popular on aerial platforms use a 4K x 4K pixel array. These do not offer a large format, so the aerial operation will be far less efficient than using a large format system and the stereo performance of such systems is inferior. Therefore such medium format cameras have been mostly used in conjunction with aerial laser scanners to augment the elevation data from the laser with color pixels. However, the images are not being used as carriers of geometric information.

Traditionally, a camera is "photogrammetric" if its interior orientation is known and stable, and if the image itself has a defined and high geometric accuracy. One traditionally expects a photogrammetric image to maintain a geometric accuracy in the range of $\pm$ 2 μm. For digital aerial cameras to be "photogrammetric", new rules are needed. Of course there is a need for careful calibration of the camera geometry. However, the concept of "inner orientation" is changed. Instead of avoiding distortion as much as possible, and instead of fiducials to defined the image geometry, the digital camera software corrects any geometric defects so that now just the geometry needs to be stable. And the inner geometry simply is defined by the pixel array itself, not by "fiducials".

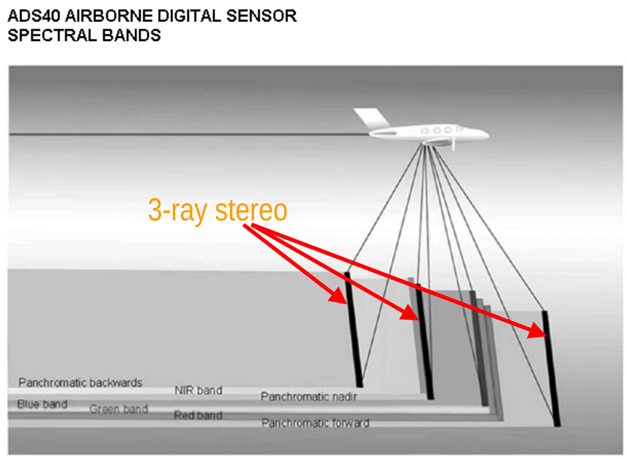
3.2 Pushbroom Technology: A Satellite Imaging Technology

The first large format camera to actually get delivered, installed and used operationally was Leica's ADS-40 pushbroom camera. This was taken from the German space program, where technology had been developed for a push broom camera to be carried on satellites. Simply commercializing a proven satellite technology seemed to be a fast way to have a product for the market, and indeed Leica's product was the first to reach the market. Figure 4 illustrates that the camera exposes at a certain moment a straight line on the ground, or multiple such lines, separately onto so-called linear arrays. By the forward motion of the airplane, sequential lines get imaged and assembled into an image strip. Each linear array exposes a "broom-like" arrangement of projection rays (therefore "brooming") and by way of the forward motion produces an image strip (therefore "push"). This strip has no internal geometry, it does not represent a photogrammetric image. The geometry of the image strip gets "rectified" by means of direct geopositioning using differential GPS and inertial measurements with an IMU, in Leica's case using the POS-AV-system by Applanix.

A fundamental element of the technology is the fact that the exposure time per pixel is not a freely selectable value, since it defines the ground resolution. At a flying velocity of 7 cm per millisecond, an exposure time of 1 millisecond will result in an image smear of 7 cm. An exposure time of 2 to 4 milliseconds is often desired and therefore the GSD is in the range of 15 cm to 30 cm. Those are values that reach into the realm of upcoming satellite sensors.

Color images by pushbrooming sensors are obtained using multiple linear arrays, one for each color band. If there is sufficient light, the exposure time for the color band and the black-and-white bands can be identical, and therefore all bands have the same geometric resolution. However, because color is the result of a filter process, less color light gets collected than panchromatic light. If one therefore sets the color band exposure time at 4 milliseconds, and the panchromatic exposure time at 2 milliseconds, then the color is at half resolution (2 x GSD) vis-à-vis panchromatic measurements.

Figure 4:
Concept of the Leica ADS40 push broom camera (from Leica's website, Leica, 2005).



3.3 Frame Imaging

The analogy with film images is a digital camera with a large frame sensor using 11,000 by 11,000 pixels. Figure 5 presents the example of Vexcel's UltraCam-D camera system. An image format of 11,500 x 7,500 pixels gets created using an assembly of 4 panchromatic lenses exposing 9 image segments that get stitched into one large seamless image. Intergraph's (2005) DMC-camera is a competing product.

Figure 5:
Vexcel's UltraCam-D camera system with the sensor unit SU, the storage and computing unit SCU, the mobile storage unit MSU for data transfer and the operator interface for on-board system supervision and in-flight quality control. To the right is a view of the 4 smaller lenses forming one large 11,500 x 7,500 pixel image in black and white, and the 4 larger color lenses for red, green, blue and near-infrared bands (for details, see Leberl et al., 2003 & Gruber et al., 2003).

The digital frame camera operates in analogy to the traditional film camera. Each image gets triggered and a single large format color image gets produced. The difference vis-à-vis the film technology is that the digital image is first collected by multiple lenses and area CCD-arrays and only a post-process then stitches the large format single image. However, the resulting large format images carry the classical photogrammetric geometric information and accuracy to within $\pm$ 2 μm.

3.4 Color Pansharpening

Satellite sensors have for a long time produced the color information at a lesser geometric resolution than the panchromatic information. Merging the two data sets results in a color image at the geometric resolution of the black-and-white panchromatic image. The process is called "pansharpening" or "fusion". A discussion of the various color acquisition technologies can be found in Leberl et al. (2002). The two currently available commercial photogrammetric large format aerial framing cameras produce the panchromatic channel at a pixel size x, and the color pixel size is y. In Vexcel's UltraCam-D, y=3 * x, in Intergraph's DMC, y= 4.5 * x.

Since color is a characteristic property of "area-objects", it is acceptable to collect color information at a reduced resolution. A variety of experiments has shown that there is no effect of the reduced resolution on any of the photogrammetric operations (see Perko, 2005).

Pushbrooming typically advertises that it produces the color at the native "high" resolution and thus avoids the process of pansharpening. However, this statement is only relevant if it is considered in the context of radiometry, which requires a certain exposure time, and this in turn affects the geometric resolution for reasons explained earlier: longer exposure, say with 2 or 4 milliseconds, produces image smear in a pushbrooming approach, and this in turn affects he geometric resolution.

4. ADVANTAGES OF THE DIGITAL CAMERA OVER FILM

4.1 Radiometry

Digital sensors collect typically 4,000 to 7,000 gray values per color channel. This is far more than the typical 256 digital values obtained from scanning film. Therefore, digital camera images vastly outperform film imagery. Using a digital camera corresponds to the use of multiple film types, both fast and slow film. The effect is a far better interpretability, better stereo matching etc.

Actually, to "view" a digital image on a monitor, projector or on film requires that one reduces the gray values to 256, thus throwing away up to 96% of all radiometric observations.

Figure 6:
Sample UltraCam Image of a snow surface in Graz (Austria, February 2005, left). Both the very bright snow (middle) and the very dark February shadows (right) are being shown with great detail.

4.2 Geometry

No film tear, no photo-laboratory, no moving parts in the camera all contribute to a superior geometric performance. However, "superior geometry" is associated with the rigorous photogrammetric imaging used in a framing camera. The pushbrooming approach does not produce images with inherent geometric accuracy – instead, the geometry is totally a function of the external measurements of the exterior orientation by the DGPS/IMU system. Geometric limits of the frame camera are in contrast solely defined by the stability vis-à-vis temperature. Aerial triangulation results routinely are being achieved with σ_0-values at $\pm$ 2 μm and better.

4.3 Color and Near Infrared

The digital camera produces with each image trigger 5 color bands: panchromatic, blue, green, red, near-infrared. With film, a pre-mission decision is needed whether to use black-and-white film, or color film, or false color film. One also needs to decide what type of sensitivity the film must have. With a digital system, these decisions are no longer necessary since each image will have the colors and infrared, and the 7,000 gray values capture the object's light as if multiple types of film had been used.

4.4 Economy

The "killer advantage" of digital camera photogrammetry is "economy". The camera itself is a self-funding investment since it gets paid from the savings on film purchases, cost of running a photo-lab and getting film developed and copied, and on savings from elimination of the need for scanning.

While these advantages seem overwhelming, the only tell part of he economic story. Once the entire workflow is digital, economic savings also become feasible after the images have been acquired, by using more automation an thus reducing the need to use labor hours, train people for many months before they can operate with the images in stereo. However, these workflow advantages need the software vendors to support the new possibilities of digitally sensed imagery. This has yet to happen.

4.5 Flight Planning

Flight planning for a framing camera is essentially identical to flight planning for a film camera. In Vexcel's case, the UltraCam-imaging layout corresponds to a film camera with a film format of 23 cm and a focal length of 21 cm. The number of flight lines is identical to a mission flown with the 21 cm focal length film camera.

The number of images obtained from the digital camera mission is greater by 1/3, simply because the image format is rectangular. However, this does not increase the data volume vis-à-vis a film data set that was scanned. Each point on the ground is covered by the same number of images as with film, but the number of files is greater over which the pixels get distributed, yet each individual file is smaller than the file from a scanned film image.

5. FROM 2-D MAPS TO 3D MODELS OF THE WORLD

5.1 Understanding the 2.5D Data Model

The traditional result form photogrammetric mapping projects are 2-dimensional data sets for input into a 2-dimensional GIS. The third dimension is only represented in the form of attributes or codes. At times this approach is denoted as "2.5 dimensional data". Traditionally, maps and the newer GIS-digital data are all presenting the world in a map projection in 2 dimensions.

In contrast, Figure 7 illustrates a fully 3-dimensional representation of a building. To the left of Figure 7 is an aerial image taken with the UltraCam system, in the center is a terrestrial image taken from the ground, and to the right is the three-dimensional representation of the building.

Figure 7:
Three-dimensional model of a building (right), obtained from aerial photography (left) and augmented with terrestrial photography (center).

5.2 The GIS versus the 3D World Model

Computer Graphics CG has never been restricted to a reduced dimension when modeling an object. As photogrammetry, GIS, and computer graphics cross into one-another's domains, traditional GIS is becoming three-dimensional. While current systems remain 2-dimensional, applications are emerging that push the GIS into the third dimension.

The real difficulty with this concept is the ortho photo. Traditionally this is a 2-d map. However, as the object models become 3-dimensional, they need to get "textured" using photographic texture. And the relationship between the geometric model and the individual photographs results in the need for a type of 3-dimensional orthophoto. Data structures have not yet been defined and agreed upon in the GIS and photogrammetry domains, yet they exist in the computer graphics domain.

5.3 Why 3-Dimensional?

The applications for 3-dimensional models are growing as a result of technology growth. In addition the rendering of objects with photographic realism is becoming more widely expected. Reading a 2D map had been an art, reading a photographically rendered model of a scene is no longer an art. This is thus a case of a "technology push": technology can do certain things, therefore they are being done, even if initially the users do not necessarily call for the capability.

However, some applications are emerging. Urban data should be 3-D, not 2D, for the variety of urban GIS applications, whether they concern city planning, citizen participation in architectural decision-making, disaster preparedness, military operations etc. Car navigation is currently strictly 2D and could benefit form the third dimension. As the systems for virtual reality and augmented reality become more widespread, terrain data are then considered "content" for such systems.

6. AUTOMATION

We have argued before that the major benefit from a fully digital workflow is not so much the economic advantage of no longer paying for film, but it is in the opportunities to automate certain photogrammetric procedures.

6.1 Film-Based Limitations for Automation

The advent of softcopy photogrammetry was heralded as the dawn of successful automation. Finally, it was argued, the scanned film images can be processed automatically into an aerial triangulation, into digital terrain models and into orthophotos, even into inputs to various 2D GIS systems. However, this promise has not been met. Errors of automated procedures have been so significant that fixing them by hand destroyed any advantage one may have had originally by the automated procedure.

Why has automation been so unsuccessful with scanned film imagery? There are three main reasons. First, film images suffer from grain noise, and this micro-detail misleads automated procedures that operate on the noise as if it was information. Second was the inability to successfully classify the terrain into different types of objects so that this can guide the automated procedures. The basic film image does not lend itself well to an automated classification of the terrain, particularly not the level of detail one would need to avoid catastrophic errors.

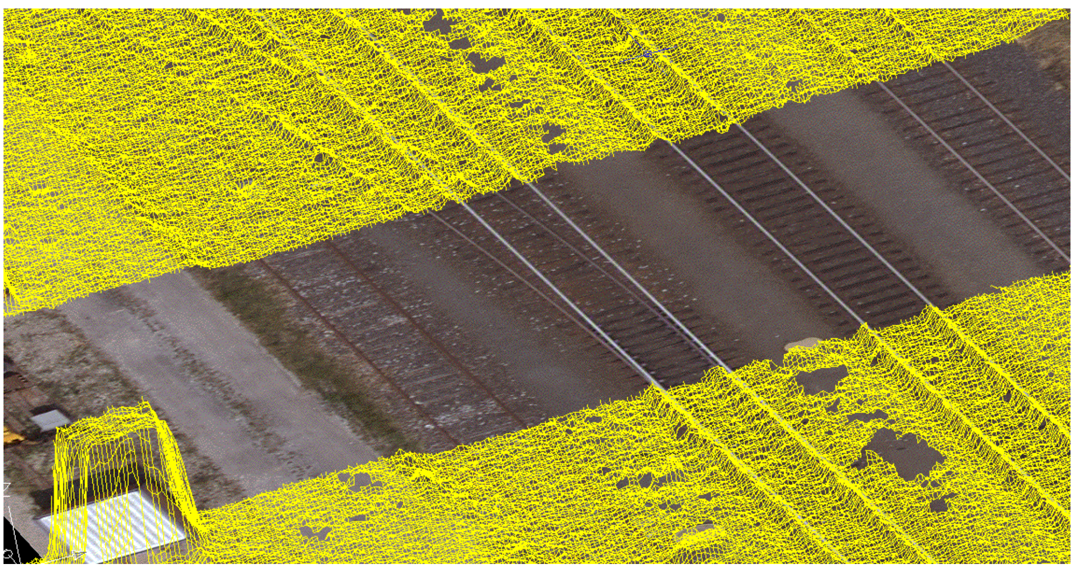


Figure 8:
Stereo-imagery at a pixel size of 3 cm, taken from a conventional survey airplane using the UltraCam-D digital aerial camera over an area at the Southern edge of Graz (Austria), and DEM extracted automatically. Note the definition of the DEM with the metal tracks elevated above the gravel bed. Point cloud from triplet of digital image set (overlap at > 70 %). Courtesy J. Jason, Vexcel Corp.

The most important factor is the third: film images do not present sufficient redundancy for automated procedures to succeed. Since the start of photogrammetry, the basic idea was always to cover the ground by two, and not more than two images, for a stereo impression by a human. The reason to limit a project to two images per terrain location was cost: more images would add cost for film, film development, scanning. Two images for stereo do not offer any real redundancy at all. When an automated procedure matches the two images and the match fails, then there is no information and the human has to step in. Since these types of mismatches happen frequently, the human participation is thus rather intensive, disqualifying the automated process. Figure 8 shows an automatically derived triangulation from images shown in Figure 1.

6.2 The Individual Digital Image Has No Cost

The digital cameras produce images with no grain noise, and with much better radiometry. These two factors help in reaching a greater level of automation, all by themselves.

However, the digital camera changes also the prevailing focus on minimizing the number of images for a project. The individual image trigger does not add any cost to image acquisition. One can produce as many images within a flight line as one wishes, with no added costs, and thus increase the traditional forward overlap from 60% to 80% or 90%. One might even consider increasing the side-lap as well, since the only cost increase would be for the additional flight lines, not, however, for the images themselves.

If one now considers that a point on the ground is not imaged merely two times, but 10 times, using a forward overlap of 80% and a side-lap of 60%, then chances for successful automation increase. Occlusions due to vegetation or buildings get reduced, an individual match of two images is no longer relevant, since if 10 images are provided, one has matches from all pair-wise combinations of the 20 images. Better yet is the use of a multi-ray matcher that considers all images of a point on the ground in the same computation.

If the aerial triangulation can be performed automatically, the DEM generated at great accuracy, with no spikes and no occlusions, and if the orthophoto mosaic can be produced as a by-product of the DEM generation, then the advantages by labor savings are much greater than the savings for the avoidance of film.

6.3 From Film Rolls to the Internet-Enabled Photogrammetric Server

The digital sensor feeds data into a “Server” which replaces the photo lab, the photo archive and also the computer center to process the images. In addition, this server is Internet-enabled and can thus support users worldwide, as a “shop” for the sales of image copies and sales of photogrammetric data products. Figure 9 illustrates the UltraMap Server, a product offered by Vexcel along with the UltraCam camera system. It is noteworthy that the Server is the computer center for post-processing the images after acquisition (the post-process to stitch the images). It also is the tool to convert the images into photogrammetric products, as the new software to perform these functions automatically slowly emerges.

These photogrammetric servers can also provide the platform for both creating and hosting 3D photogrammetric products allowing web access to navigate models of unprecedented reality. Figures 10 and 11 illustrate two web-based views into such a sample product (Graz, Austria, June 2005). Note the commercial potential of providing such an abundance of natural cues (both aerial and street level) to the location of what would otherwise be an obscure shop.

7. SATELLITE IMAGING VERSUS AERIAL PHOTOGRAMMETRY

GSD-capabilities of satellite sensors are improving. Digital Globe’s Quickbird images have a maximum resolution on the ground of 60 cm, the Ikonos data by Space Imaging are in the range of 80 cm to 1 m. Current projects call for even higher resolutions in the range of 30 cm pixel sizes. This may seem as if it starts to seriously compete with aerial camera coverage. However, it does not.

Satellite images have to contend with several issues that are not a problem for aerial sensors. The most important are:

- Weather
- Multiple coverage for stereo and to achieve redundancy
- Response time between expression of need and delivery of data
- Cost per data unit
- Limits on the GSD

The weather dictates the time it takes to obtain coverage. The option of flying under the clouds does not exist. Multiple coverages for stereo and to achieve a 5-times to 10-times redundancy are obstructed by cost and weather. Weather and coverage constraints dictate the time between a data order is issued and data get actually collected. Cost is an issue that is very flexible in aerial surveys due to the cost structure of aerial systems. Typically an aerial survey is less expensive than data from satellites. Finally there is an advantage for aerial surveys that GSD-values of 3 cm are feasible and useful. For an aerial system, pixel sizes of 30 cm or 60 cm are large.

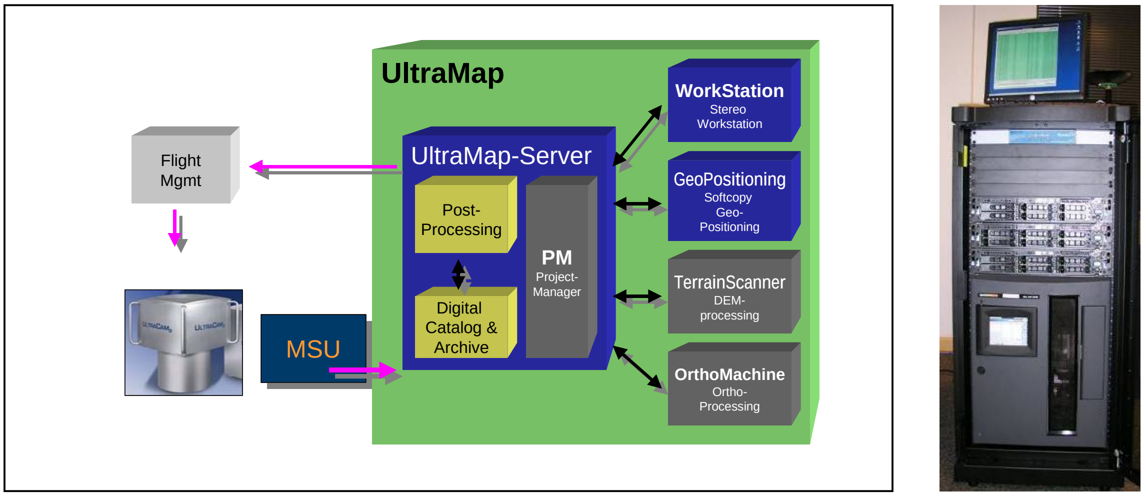


Figure 9:
The Server replaces the photo lab, the roll film archive, the computer center and the "shop" for sales of film images. To the left is the functional diagram embedding the Server in the entire workflow from flight planning to final product delivery. To the right is an image of the 500-kilogram-Server in a rack, operating with up to 200 tapes for near-line storage of more than 200,000 digital images, and with 4 CPUs or various processing tasks.

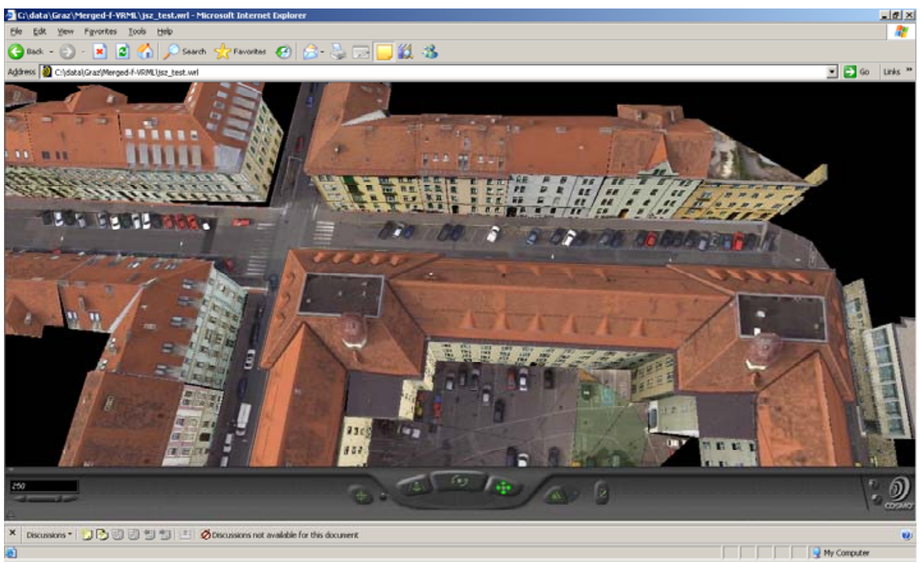


Figure 10:
"Helicopter-view" of the 3D digital model of a scene in Graz, Austria, based on aerial imagery taken with the UltraCam-D camera. This view is available interactively via the Internet.

8. CONCLUSIONS

We present facts explaining the reasons for the rapid acceptance of the novel digital aerial cameras. The main group of reasons deals with the sensing process itself. First, the transition to digital can be self-funding, simply by eliminating the costs for film, film processing and scanning. Second, digital sensors produce superior quality imagery without film's notorious grain noise, and with 13 bit radiometry (7,000 gray values) as opposed to film's 8-bit radiometry (256 gray values). Third, they produce additional information in the form of a near- infrared band. Forth, the fully digital workflow provides superior in-flight and post-flight quality control. Fifth, the overall workflow as it is being used today with scanned film, can be maintained and here is no need for a "revolutionary" replacement of all legacy approaches and tools by the new technology.

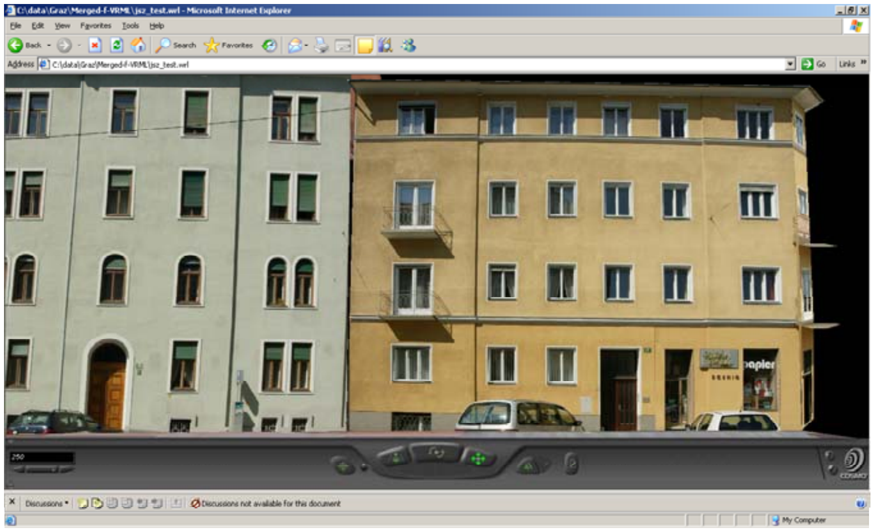


Figure 11:
Ground view of the digital model in Figure 9 (Graz, Austria). This view employs ground based photography to augment the aerially generated scene model. Again, this view is available interactively via the Internet.

There is a secondary group of reasons why the fully digital workflow is attractive. This has to do with the automation of the photogrammetric procedures. While this full automation requires changes in the mission planning to produce more images than was the case with film, these new images do not add cost, yet they support automation. And the automation in turn not only reduces costs for labor, it also makes it feasible to offer new data products such as fully 3-dimensional models of urban scenes, resulting in a “virtual habitat” in lieu of the traditional 2-dimensional maps and GIS.

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