Digital photogrammetric cameras: possibilities and problems

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ABSTRACT

Airborne digital sensors are about to widen the choices in photogrammetry. The transition from analytical to digital photogrammetry is well advanced and the dividing lines between photogrammetry and remote sensing grow increasingly blurred. One of the advantages of direct digital data capture in the air is the possibility of capturing multispectral data as well as panchromatic. Positioned between modern film-based aerial mapping cameras with their extremely high resolution and, at the other end of the spectrum, the forthcoming high-resolution satellite sensors, the new airborne devices can access a large market.

Two technologies are available as the basis for airborne digital sensors – linear and area array CCDs. The performance of the latter is insufficient to offer swath widths and resolutions comparable to film cameras. The most promising alternative appears to be linear arrays, arranged in a triplet on the focal plane, one forward-, one nadir- and one backward-looking. When combined with GPS and INS systems, this configuration provides geometric performance that enables the same photogrammetric operations to be performed on the workstation as with scanned film imagery. Radiometric issues such as the signal to noise ratio must be fully taken into account. Moreover, multispectral CCD lines can also be placed on the focal plane, providing data tractable by image processing techniques from remote sensing, with the additional advantages of geometrically correct sensor modeling, stereo imagery and accurate geocoding.

A development project between LH Systems and the German Aerospace Centre has resulted in a functioning three-line sensor. An engineering model has flown successfully and a production model is scheduled for market introduction in summer 2000.

1. INTRODUCTION

LH Systems' announcement at the end of 1998 that an engineering model of their forthcoming airborne digital sensor had been flown successfully implies that a genuine alternative to the familiar aerial film camera is imminent.

Except for producing stereoscopes, LH Systems and its predecessor Leica were never active in image interpretation. Yet this new sensor will have multispectral lines on the focal plane: it will be capable of generating precise, geometric information about the surface of the earth, but will also produce data amenable to proven remote sensing techniques. It will further soften the demarcation between photogrammetry and remote sensing and accelerate the decline of the photo laboratory, as digital image data can be transferred from the aircraft directly to the workstation.

The debate about airborne versus spaceborne imagery continues. The highest resolution applications, with ground pixel sizes in the one centimeter to one decimeter level, are likely to remain the province of the film camera. Yet there is a huge, pent up demand for top quality, multispectral information in the gap between this and the one meter and coarser resolutions offered by the satellite operators. Both spaceborne and airborne sensors have their advantages and the most likely scenario for the future will be an increased emphasis on data fusion as users select the sensors most likely to provide their information in each case and rely on their workstation software to use all the data together. The two types of data will be complementary rather than competitive.

2. AIRBORNE DIGITAL SENSORS – THE REQUIREMENTS

To have any chance of an impact in a market place spoilt for decades by high performance film cameras, an airborne digital sensor must provide:

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- Large field of view and swath width
- High resolution and accuracy, both geometric and radiometric
- Linear sensor characteristics
- Multispectral imagery
- Stereo.

The first requirement, however, seems to rule out area CCD arrays, because readily available models in mid 1999 are 4K x 4K pixels or less, whereas a linear array of 12 000 pixels is readily available, requiring only one third as many flight lines. Considerable research work has been done in Germany since the 1970s, which has demonstrated the suitability of three panchromatic lines on the focal plane, with additional multispectral lines near the nadir. This obviates the need for multiple area arrays to provide a wide field of view and a multispectral capability (Figure 1).
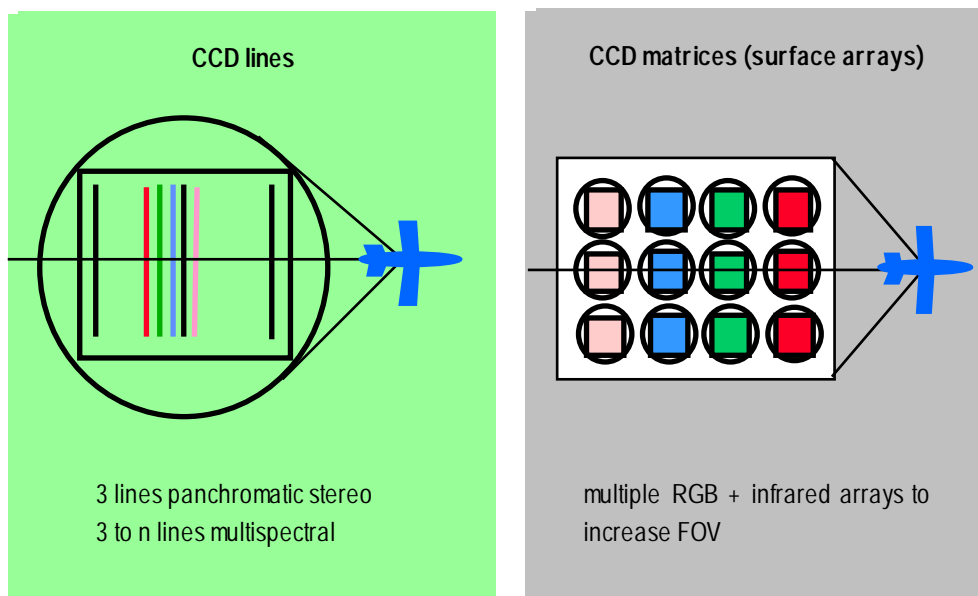

Figure 1: The alternatives: The left-hand diagram suggest how the focal plane could be populated using the three line principle: three panchromatic lines give the geometry and stereo, whilst additional lines, their sensitivity controlled by filters, give the multispectral information. In the right hand diagram, multiple area array CCDs and lenses are required to provide both the same ground pixel size and multispectral range as the three-line approach.

3. THREE-LINE SCANNER APPROACH

The three-line concept results in views forward from the aircraft, vertically down and looking backwards (Figure 2). The imagery from each scan line is assembled into strips (Figure 3). The characteristics of relief displacement in the line perspective geometry of the strip approach *vis a vis* the conventional central perspective geometry are indicated in Figure 4.

The angles between the incoming information to the three lines are, of course, fixed. With three lines there are three possible pairings for stereoscopic analysis – strips 1 and 2, 2 and 3, and 1 and 3. With film cameras, the parallactic angle is a function of principal distance and airbase. Moreover, every object appears on all three strips, whereas on film imagery only 60 % of the area of any one photograph is in a triple overlap.
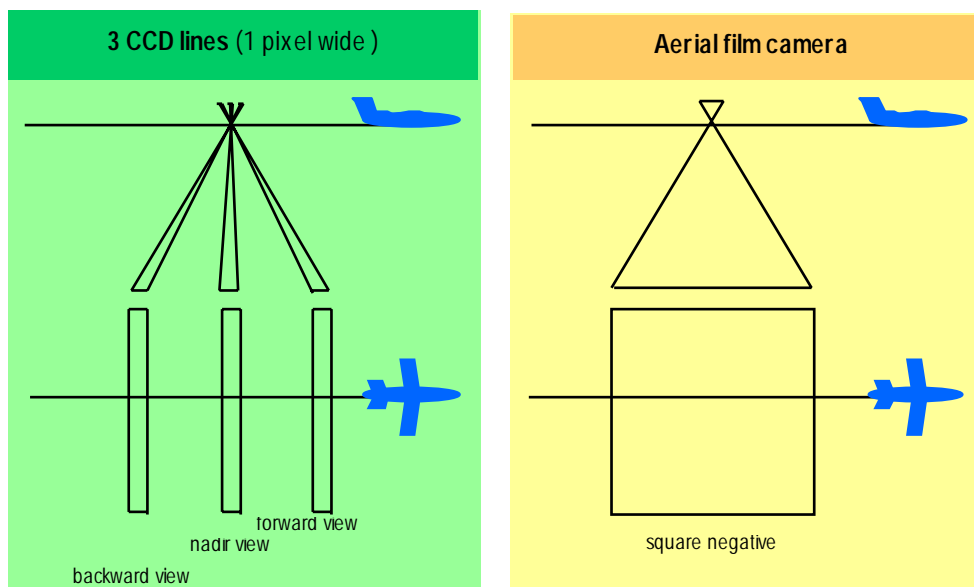
Figure 2: Basic geometric characteristics of three-line digital sensor and film camera.
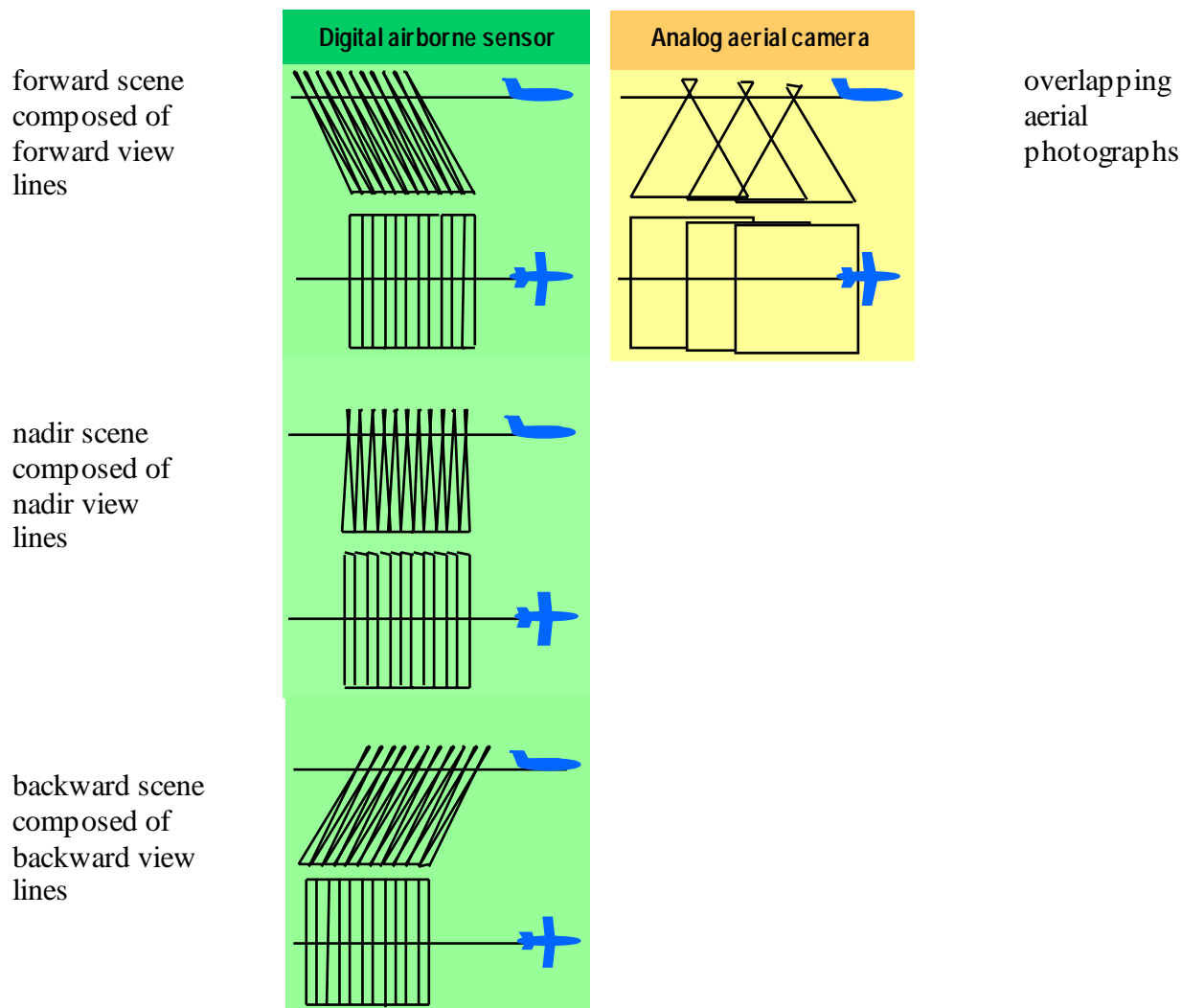

Figure 3: Comparison of the acquisition of scenes by three-line digital sensor and film camera.

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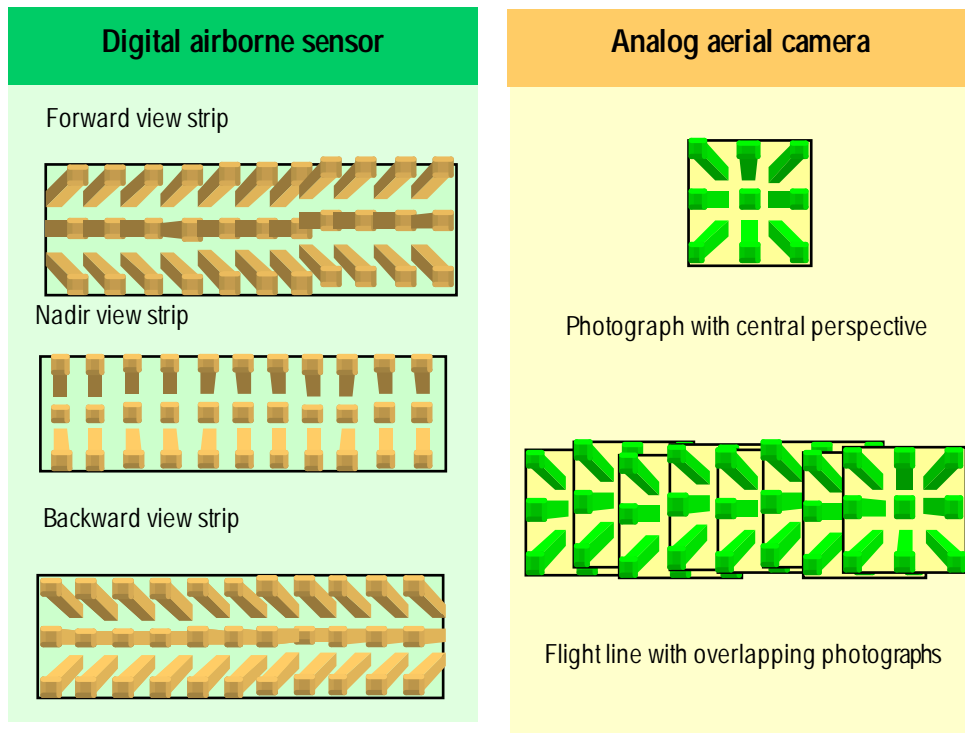| Digital airborne sensor	Analog aerial camera
Forward view strip	
	Photograph with central perspective
Nadir view strip	
Backward view strip	Flight line with overlapping photographs

Figure 4: Effect of terrain relief on the imagery showing the line perspective
geometry of the three-line imagery on the left and the familiar central
perspective geometry of the film photograph on the right.

4. RADIOMETRIC CONSIDERATIONS

The best possible signal to noise ration (SNR) is a precondition for signal processing, digitizing, data compression and data transfer with little interference. The signal to noise ratio of the elements of a CCD are given by:

$$SNR = \frac{n_s}{\sqrt{\sigma_s^2 + \sigma_{rms}^2 + \sigma_{fp}^2}} \tag{1}$$

where n_s :   Signal electron count,

σ_s^2 :   Variance of signal electron count,

σ_{rms}^2 :   Variance of the time dependant noise,

σ_{fp}^2 :   Variance of local sensitivity differences (fixed pattern noise).

The signal electron count is directly proportional to the number of arriving photons (within a defined narrow wavelength interval). The noise of the signal electrons therefore is subject to the Poisson statistics of photon noise:

$$\sigma_s = \sqrt{n_s} \tag{2}$$

The time dependent noise of the CCD and of the analog channel (rms noise) contains:

- Temporary dark signal noise (Poisson statistic)
- Reset-noise and on-chip-amplifier noise ("kTC-noise")
- Transfer noise
- Other electronic noise (1/f - noise, thermal noise).

For estimation purposes the following calculations are based on a noise electron count of
$\sigma_{rms} = 235 e^-$.

The fixed pattern noise has two sources

- Photo response non-uniformity (PRNU) of the CCD elements
- Shading of the light intensity in the focal plane of a wide-angle optics

Observing the behavior of only one CCD element by ignoring the PRNU (photo response non-uniformity), e.g. the fixed pattern noise, we find the conditions shown in Figure 5, if we take into account a saturation electron count of >500 000. The SNR amounts to 8 or 9 bits (SNR = 250 ...670) for an electron count >100 000.
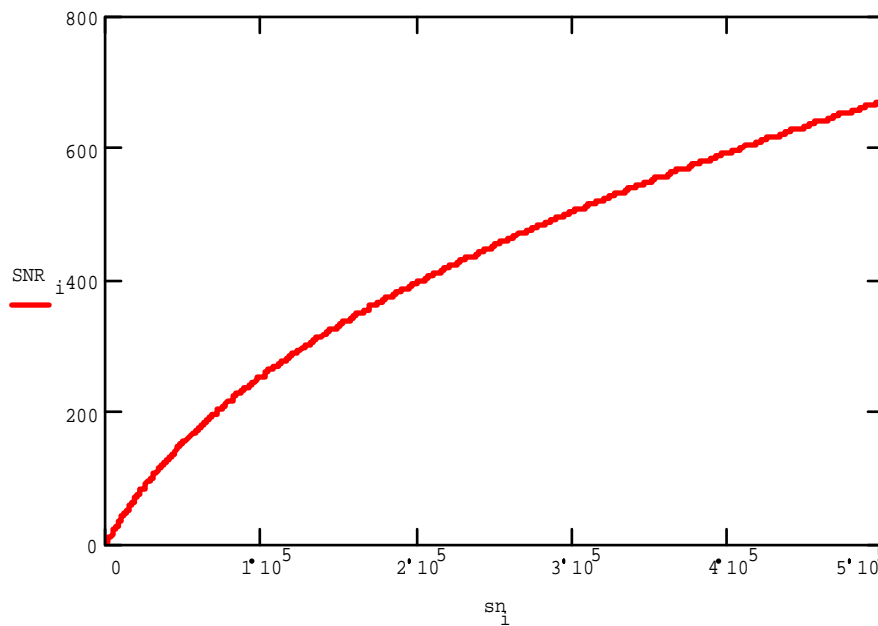

Figure 5: SNR of one CCD-Element at a saturation load of 500 000 electrons
and a rms-noise of 235 electrons.

If we now look at the real conditions in the focal plane of a wide-angle lens, we obtain the diagram of the signals at the outlet of a CCD line, as shown in Figure 6.
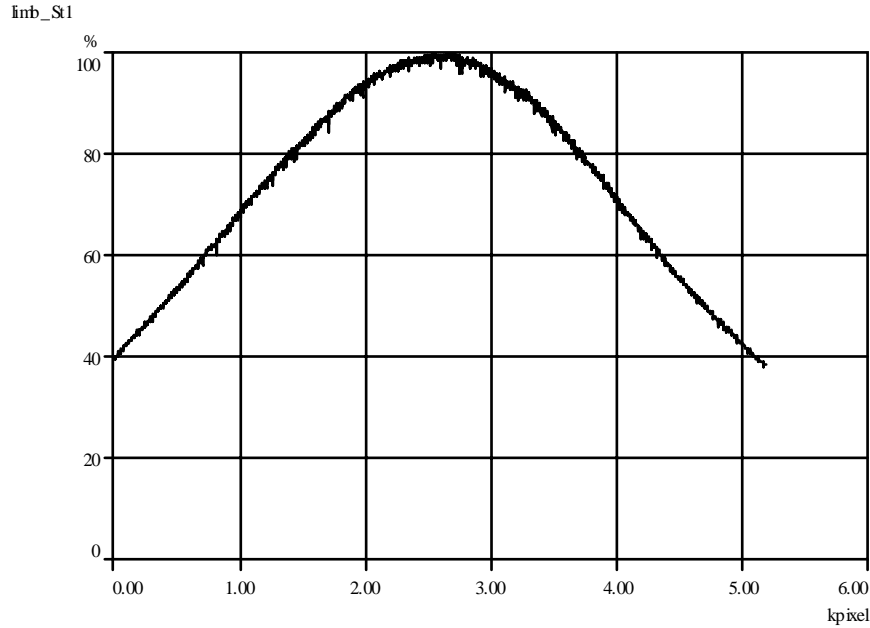
limb_St1

Figure 6: Flat field illumination creates in the focal plane of wide-angle optics
a CCD signal including the effects of shading due to optics and PRNU.

One can clearly see the effect of the shading of the lens (at the edges the light intensity falls off to about 40 %) and of the influence of the PRNU. The differences of sensitivity of CCDs are usually indicated in the datasheets as PRNU values in percent of the values of the videocurrent for the range far below saturation (mostly at 50 % of U_{sat}). We will adhere to this definition here as well. Thus in the linear range of the CCD the fixed pattern noise of the pixel sensitivity can be expressed directly as a signal dependent noise, which is converted into a time dependent noise during transfer of the charge.

$$\sigma_{fp} = \frac{PRNU}{100\%} \cdot n_s = \frac{PRNU}{100\%} \cdot \sigma_s^2 \tag{3}$$

Depending on the PRNU of the CCD the signal to noise ratio results as:

$$SNR = \frac{\sigma_s}{\sqrt{1 + \left[\frac{PRNU}{100\%} \cdot \sigma_s\right]^2 + \left[\frac{\sigma_{rms}}{\sigma_s}\right]^2}} \tag{4}$$

Figure 7 shows graphically the highest attainable SNR at full exploitation close to saturation (400 000 to 500 000 signal electrons) in relation to PRNU, based on the aforementioned parameters. Up to a PRNU value of 0.02 % the SNR is determined exclusively by the photon noise of the signal, the rms noise of the CCD and the noise of the analog channel. At 0.1 % the PRNU influence becomes dominant. In the engineering model of LH Systems' new airborne digital sensor, described in sections 6 and 7 below, the PRNU correction is done pixel-wise.
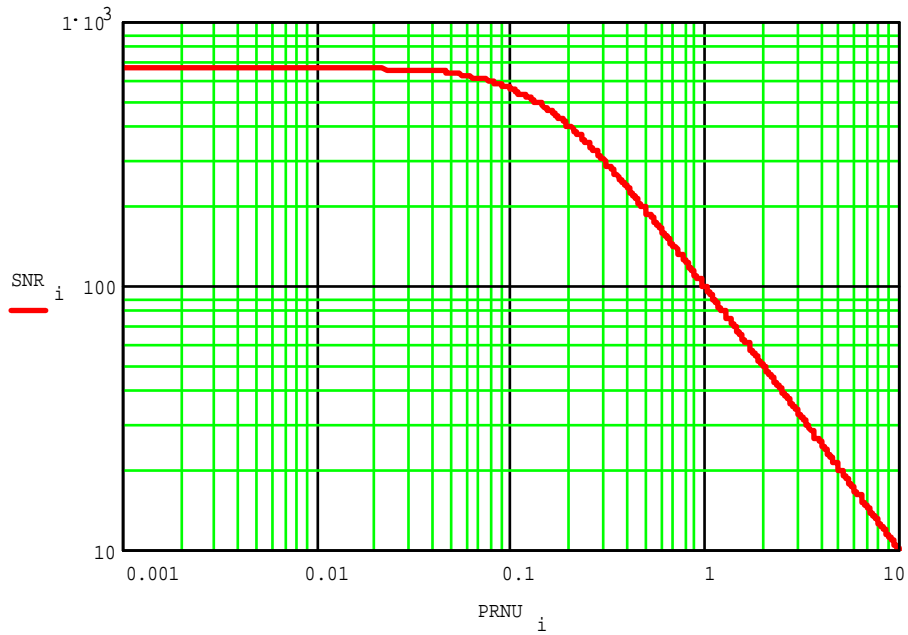
Figure 7: SNR in relation to PRNU assuming a thermal and electronic noise of
$S_{el} = 235$ rms-electrons and a signal electron counts of $500\,000$ e⁻.

Normally light fall-off of the lens system (approximately 30 %) is corrected simultaneously with the PRNU correction. For the estimation or the PRNU correction, this light fall-off has not been taken into account because it does not contribute directly to an increase of the SNR. Light fall-off only contributes indirectly through the adaptation of the signal to the analog channel. The correction of light fall-off of the lens does not restrict the SNR significantly.

The efficiency of the correction can be seen very clearly in Figure 8. In the radiometrically zoomed-out image parts no noise can be seen.
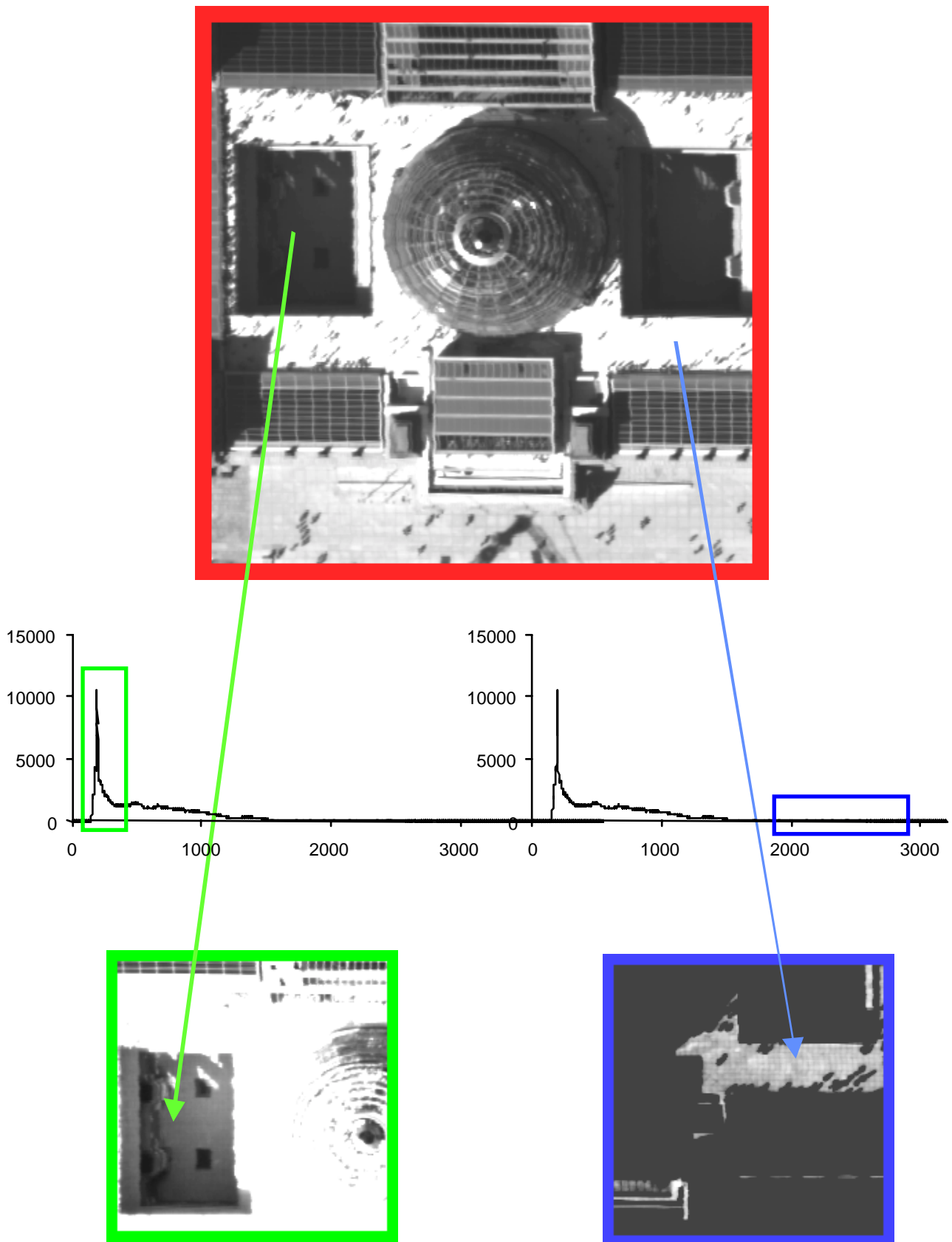
Figure 8: Imagery of the Reichstag, Berlin, taken with the engineering model of the
LH Systems airborne digital sensor on 23 April 1999. The flying height is 3 km
and the ground sample distance is 0.25 m.

5. IMAGE PROCESSING

The bizarre appearance of raw imagery, owing to aircraft tilts and terrain relief causing the linear arrays to image widely varying strips of terrain (Figure 9), is well known. Tilts can be compensated by adjusting each individual scan line for the attitude of the aircraft, using data from the airborne GPS and INS units carried on every fight. An initial rectification using these data is essential even to view the imagery. Thereafter, operations such as triangulation, DTM measurement, orthophotos and feature extraction continue in the usual way. Automated processes, such as point measurement for triangulation and DTM extraction, can be based on triplet matching using the three strips.
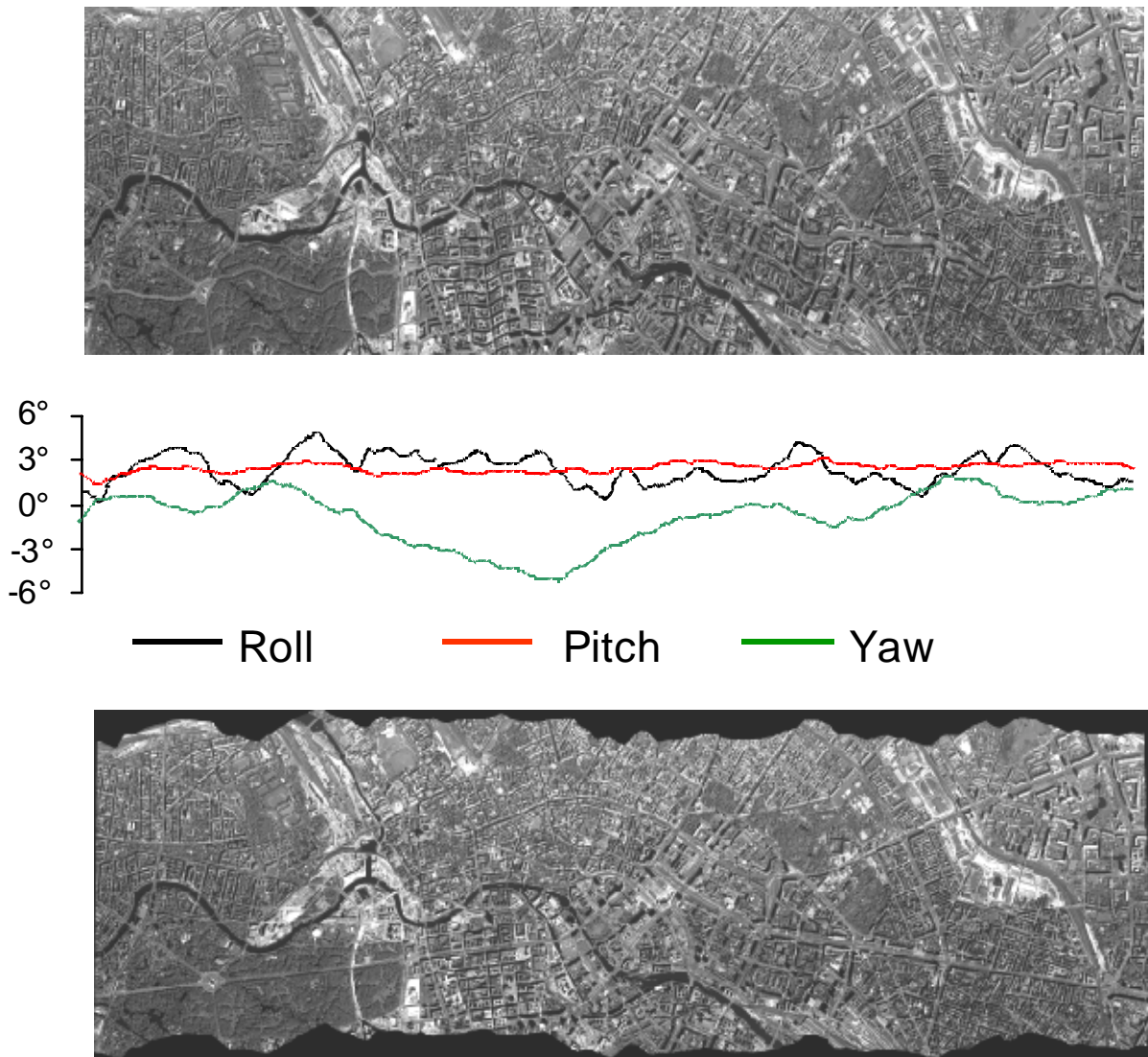

Figure 9: Imagery acquired by the new sensor over Berlin. The flight direction was from left to right. The top image is raw. The bottom image has been rectified and looks similar to a conventional aerial photograph. Note the correspondence between the edges of the rectified image and the roll of the aircraft.

Owing to their positions on the focal plane, combined with the aircraft and terrain variations, the color lines image slightly different parts of the earth's surface. Thus full rectification is required, i.e. orthophotos are produced, before the color bands can be properly registered and ransformed into color composite images suitable for analysis by off-the-shelf remote sensing packages.

6. ENGINEERING MODEL AND TECHNICAL CO-OPERATION

The complexity, cost and difficulty of developing and manufacturing a novel airborne digital sensor ruled out "going it alone". In early 1997, shortly before LH Systems was formed, Leica Geosystems reached a technology agreement with Deutsches Zentrum für Luft- und Raumfahrt (DLR), the German Aerospace Centre in Berlin. This provided for long term co-operation, with joint development by both parties and assembly by Leica Geosystems. DLR's experience in this area is unparalleled. Amongst a host of intricate and impressive achievements in both airborne and spaceborne technology, it made historic progress with sensors based on the three-line approach (Table 1), for example the WAOSS (Wide Angle Optical Stereo Sensor, built for the unfortunate Mars-96 mission) (R. Sandau and A. Bärwald, 1994), WAAC (Wide Angle Airborne Camera) (R. Sandau and A. Eckhardt, 1996) and HRSC (High Resolution Stereo Camera) (J. Albertz, H. Ebner and G. Neukum, 1996). The technical and performance data of WAOSS and WAAC are summarised in Table 1. This expertise complemented well Leica Geosystems' abilities in optics, mechanics and electronics, together with its deep appreciation of customers' requirements acquired through decades of producing aerial film cameras. It was natural that the agreement between the parties be transferred to LH Systems quite soon after its formation.

	WAOSS	WAAC
Focal length, f	21.7 mm	21.7 mm
FOV (across the track)	$\leq 80^0$	$\leq 80^0$
Optics	Spitmo- Russar-96	Spitmo- Russar-96
Number of CCD- lines	3	3
Spacing of CCDs	10.1 mm	10.1 mm
Convergence angle	25^0	25^0
IFOV (quadratic)	3.23×10^{-4} rad	3.23×10^{-4} rad
Elements per CCD-line	5184	5184
Elements spacing	7 µm	7 µm
According to platform height	Hn = 250 km	H = 5 km (v = 200 km/h)
Swath width (nadir CCD)	420 km	8.4 km
Minimum ground resolution - in line direction - in trajectory direction	 80 m 80 m	 1.6 m 1.6 m
Dynamic range	11 Bit	11 Bit
Radiometric resolution	8 Bit	8 Bit
Spectral channel - nadir - forward, backward	 470...670 nm 580...770 nm	 580...770 nm 470...670 nm
Data compression factor	2...20	2...20
Data compression method	DCT- JPEG	DCT- JPEG
Output science data rate	100...500KBit / s	100KBit / s...24MBit / s
Physical dimensions	L:373 x B:190 x H:218 mm	L:285 x B:190 x H:202 mm
Mass	8 kg	4.4 kg
Power	18 W	15W

Table 1: Technical and performance data of Wide- Angle Optoelectronic Stereo Scanner (WAOSS) and Wide- Angle Aircraft Camera (WAAC).

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7. PRACTICAL CONCLUSIONS

The features of the film and digital approaches are compared in Table 2. LH Systems has chosen the three-line scanner approach for the reasons given above. The engineering model has flown (Figure 10, Table 3) and work is proceeding towards the production model, which will have at least 20 000 pixels in each line, faster integration times and multispectral bands.

This is on schedule for launch at the ISPRS Congress in Amsterdam. The formidable technical challenges can be met. Perhaps the real hurdle will by then have moved: photogrammetrists will learn to work with imagery that is strikingly different in appearance from the film case and is processed using unfamiliar sensor models. They will be able to share data with the remote sensing community and for the first time create deliverables with both the depth of information accruing from image understanding of multispectral images and the geometric fidelity of photogrammetry.

Characteristic	Aerial film camera	Airborne digital sensor
Flying time	20 % less	-
Photo lab	Yes	No
12-bit in-flight sensing	No	Yes
8/10-bit scanning	Yes	Unnecessary
Data volume	20-50 % less	
Pre-processing	No	Yes
GPS	Yes (optional)	Yes
INS	Unusual	Yes
Projection centers	Interpolated (few)	Interpolated (many)
Ground control points	Yes, but hardly any with GPS	Yes, but hardly any with GPS
Tie point matching	Few – between images	Many

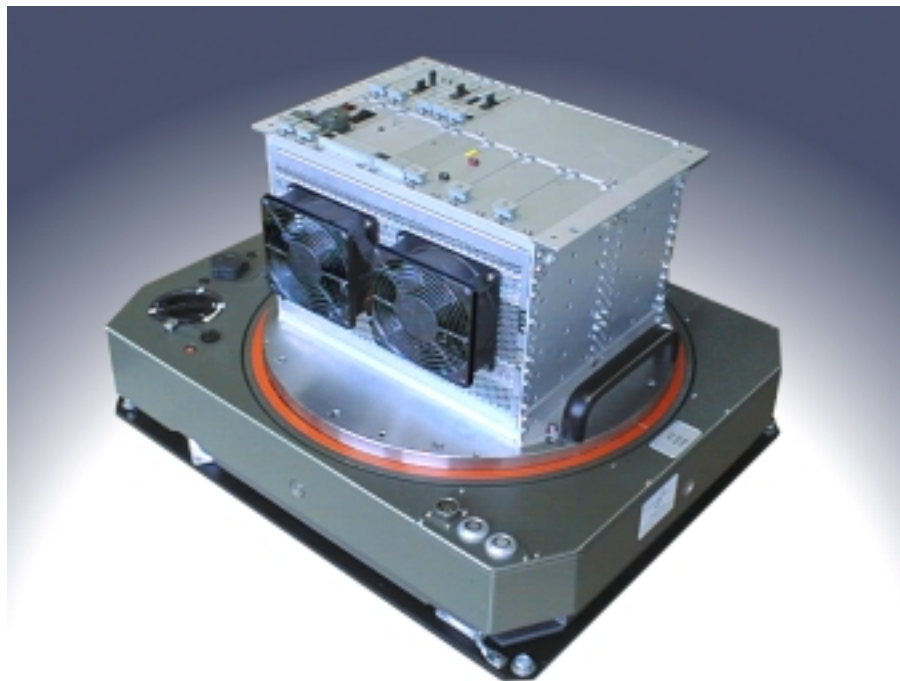Table 2: Features of aerial film camera and airborne digital sensor.

Figure 10: The engineering model of LH Systems' airborne digital sensor, which
was successfully flown in late 1998.

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General	
Principle	3 line CCD stereo sensor
Pixels per CCD Line	12 000
Pixel size	6.5 µm
Dynamic range	12 bit (raw data mode)
Radiometric resolution	8 bit
Normalization mode	8 bit linear or non-linear
FOV (across track)	52°
Focal length	80 mm
Swath at 10,000' flying height (3,100 m)	3 000 m (1.9 miles) and 25 cm ground pixel size
Stereo angles	17°, 25°, 37°
Recording interval per line	1.2 ms
Filter range (at λ50)	Panchromatic, 465nm – 680nm
Power	
Input voltage	28 VDC or 220 VAC/50 Hz
Consumption / average (peak)	Engineering model: 600 W (1000 W)
	Mass memory system: 600 W (600 W)
	ASCOT: 80 W (180 W)

Table 3: Specifications of the engineering model.

8. REFERENCES

Albertz, J., Ebner, H. and G. Neukum (1996): The HRSC/WAOSS Camera Experiment on the MARS96 Mission – A Photogrammetric and Cartographic View of the Project, 18th ISPRS Congress, Vienna, July 9-14.

Sandau, R. and W. Bärwald (1994): A Three-Line Wide-Angle CCD Stereo Camera for Mars-94 Mission, International Archives of Photogrammetry and Remote Sensing, Vol. 30, Part B1, pp. 82-86.

Sandau, R. and A. Eckardt (1996): The Stereo Camera Family WAOSS/ WAAC for Spaceborne/Airborne Applications, International Archives of Photogrammetry and Remote Sensing, Vol. 31, Part B1, pp. 170-175.