Film Cameras or Digital Sensors? The Challenge Ahead for Aerial Imaging*

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Abstract

Cartographic aerial cameras continue to play the key role in producing quality products for the aerial photography business, and specifically for the National Aerial Photography Program (NAPP). One NAPP photograph taken with cameras capable of 39 ℓp/mm system resolution can contain the equivalent of 432 million pixels at 11 μm spot size, and the cost is less than $75 per photograph to scan and output the pixels on a magnetic storage medium.

On the digital side, solid state charge coupled device linear and area arrays can yield quality resolution (7 to 12 μm detector size) and a broader dynamic range. If linear arrays are to compete with film cameras, they will require precise attitude and positioning of the aircraft so that the lines of pixels can be unscrambled and put into a suitable homogeneous scene that is acceptable to an interpreter. Area arrays need to be much larger than currently available to image scenes competitive in size with film cameras.

Analysis of the relative advantages and disadvantages of the two systems show that the analog approach is more economical at present. However, as arrays become larger, attitude sensors become more refined, global positioning system coordinate readouts become commonplace, and storage capacity becomes more affordable, the digital camera may emerge as the imaging system for the future. Several technical challenges must be overcome if digital sensors are to advance to where they can support mapping, charting, and geographic information system applications.

Introduction

A new technology tends to evolve through a typical development cycle: initial discovery and excitement are followed by a lengthy period of research and development and tutorial sessions until the technology finally begins to appear in systems for practical applications. Then, if successful, the technology may experience rapid growth. The new technology becomes successful only if it offers clear advantages over the current approach. In the mapping field, aerial film cameras have improved to the point where they are approaching a mature technology. Electro-optical scanners and digital sensors (charge coupled devices (CCD)) also are used for remote sensing. For example, they are being used for military applications where real-time aerial images are essential. In the civil community, practically all images used in photogrammetric applications are captured on film. Even though film camera technology prevails, the mapping, charting, and geographic information system industry is going digital. If digital photogrammetric techniques are applied, the film image must be scanned and digitized into machine readable picture elements (pixels) and stored on a media such as tape, disks, or CD-ROMs. The obvious question is: Will airborne digital sensors that output directly in digital format replace the aerial film camera in the near future? Hartl (1989) of the University of Stuttgart wrote: "It is expected that, with the progress in electro-optical developments, pushbroom cameras will gradually replace photographic cameras." The words "gradually replace" are important because film cameras are still improving with computer designed lenses, forward motion compensation, and angular motion stabilization. These are necessary for the aerial film camera to become a mature technology. Then the mature technology film camera can be expected to deliver to the user a system resolution of about 39 ℓp/mm. This is a 30 percent increase in image resolution over what was expected a few years back, and in reality sets the standard by which digital sensors will be measured. It will cost less than $100 per frame to convert the film to digital pixels and a storage medium, and from then on the data are digital. So the challenge ahead for builders of digital sensors is to create a better product for the user than that offered by aerial film camera technology.

To form a basis for comparison, an analysis of aerial film camera technology and the techniques for digitizing the photographic image into digital pixels follows. A similar analysis of digital sensors provides the information for comparing the two types of competing sensors and points out the challenge ahead for the newest technology. Over the next few years, users with nonmilitary applications will continue to depend on the time-proven film camera. But, eventually, digital sensors are expected to become very competitive.

Aerial Film Cameras and Digitized Pixels

An aerial film camera, such as those flown for the National Aerial Photography Program (NAPP) (Light, 1993), has a focal length of 152 mm (6 inches) and a 230- by 230-mm (9- by 9-inch) film format where the whole photographic scene is recorded on one homogeneous 230- by 230-mm frame of film at the instant of exposure. The exposed film can be thought of as a nearly infinite number of focal-plane detectors, because each ground-resolution element will cause a corresponding reaction on the film, with no overlap. This is why high-resolution film currently produces the best resolution attainable of all remote sensing schemes. A figure of merit for measuring resolvability of the film camera system is the area weighted average resolution (AWAR). The system's AWAR is given in line pairs per millimetre (ℓp/mm). A line pair is

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the width of one black bar and one white space as contained on resolution targets. Together, they form a pair and serve as a measure of image quality for the aerial film camera industry. The five essential elements that make up the system AWAR are the lens, original film, image blur (smear) on the film due to aircraft forward velocity, angular motion, and the resolution of the duplicating film. Also, the scene contrast of the Earth and the atmosphere play a key role in system resolution, but, unfortunately, the latter two are uncontrollable factors in sensor system design. Table 1 shows the dramatic improvement in the AWAR and the reduction of geometric distortion that has occurred in cameras calibrated at the U.S. Geological survey since the 1960s. The improvement is largely attributed to computer lens design. Even with this increase in laboratory-determined static resolution, experience has shown that the atmosphere and other attenuating factors, in flight, always reduce final film resolution to less than 40 ℓp/mm.

Motion Compensation

The need to compensate for forward and angular motion in the aerial photograph is not new to the aerial camera industry. The Aeroflex Laboratory Inc. (Trott, 1960) experimented with stabilizing platforms, and in the early 1960s Fairchild Industries developed their KC-6A aerial camera with forward motion compensation (FMC). Then in the late 1970s NASA developed its Large Format Camera (LFC) for a space shuttle mission. The LFC, built by Itek with forward motion compensation, had its flight on the space shuttle in 1984. Neither of these developments became commercially available. It was not until 1982 that Zeiss Jena, now Carl Zeiss, introduced the first commercially available aerial camera with FMC (Diete, 1990), followed in 1990 by a gyro-stabilized mount for stabilization of angular motion (Klose, 1990). FMC and angular motion control (AMC) improvements are expected in 1994-95 from two commercial camera manufacturers, Carl Zeiss of Germany and Leica, Wild of Switzerland. These two improvements, FMC and AMC, were the two remaining areas where significant contributions toward improving image quality could be accomplished. Appendix A demonstrates the use of NAPP mission characteristics to compute a forward motion blur of 12 μm in a typical NAPP photograph.

As a rule of thumb, when image blur is less than half of a resolution element (1 ℓp), it is not beneficial to compensate for forward motion. In the case of future NAPP photographs where 1 ℓp will equal 25 μm in the image, FMC may be unnecessary when using film with an effective aerial film speed of 200 or higher.

While FMC for NAPP cameras flown at an altitude 6,000 m (20,000 ft) may be unnecessary, control of angular motion may be beneficial. The effects of angular motion due to roll, pitch, and yaw of the aircraft inflight smears the image and, therefore, effects the resolution of the photograph.

Equations were derived by Kawachi (1965) to provide a basis for a rigorous analysis of *xy* coordinate movement on the image due to changes over time in roll ($\dot{\omega}$), pitch ($\dot{\varphi}$), and yaw ($\dot{\kappa}$) of the aircraft. Appendix A uses these equations to analyze the effects on NAPP photographs. For a typical NAPP photograph taken with state-of-the-art cameras, the image blur due to angular motion is 21 μm or 48 ℓp/mm.

Camera System Resolution

The combined influence of the lens, the original and duplicate films, forward motion, and angular motion on the total system resolution can be approximated (Meier, 1984; Kawachi, 1965). (See Appendix A for these approximations.)

For NAPP images, depending on scene contrast, it is reasonable to expect 39 ℓp/mm for low contrast scenes and up to 54 ℓp/mm for high contrast scenes with today's aerial cameras that have both FMC and AMC that minimize motion effects on resolution. Considering the lower estimate to cover the Earth as a low contrast scene, the camera system resolution of 39 ℓp/mm yields approximately 25 μm for the size of 1 ℓp in the image. At 1:40,000 scale, 25 μm equates to a ground resolution of 1 m for low-contrast scenes; therefore, a minimum of 1-m ground resolution can be expected throughout the photographic mission. The maximum for high-contrast scenes would be 0.7 m.

TABLE 1. AERIAL CAMERA TRENDS

Year	AWAR (ℓp/mm)	Geometric distortion (μm)
1960	63	±10
1994	95+	±3

Scanning Aerial Film for Digital Pixels

One significant advantage of aerial film cameras is that the entire 230- by 230-mm frame is exposed at one instant making the entire frame one homogeneous unit imaged by, in effect, an infinite number of detectors. Converting this frame to pixels for use in digital photogrammetry requires precise scanning at the appropriate pixel size to minimize resolution losses and approximately preserve the film resolution inherent in the image. The smaller the pixel, the more computerized storage capacity is needed to hold the digital data. Film is a dense storage medium that yields millions of pixels when scanned. The pixel data are merely digital representations of photographic images, but they are in computer-readable form ready for use in digital photogrammetry.

Computing Appropriate Pixel Size

The resolution attainable in the NAPP with cameras such as the Leica-Wild RC-30, Zeiss Top-15, or LMK-2000 is estimated at 39 ℓp/mm, which is approximately 25 μm on the film for 1 ℓp. Employing a method published by Light (1993) that uses the Nyquist sampling theory and the Kell factor, the range of acceptable spot size to preserve the film resolution can be computed as follows:

$$\frac{25\ \mu\text{m}}{2\sqrt{2}} \le \text{Scan Spot Size} \le \frac{25\ \mu\text{m}}{2}.$$

Then

$9\ \mu\text{m} \le \text{Scan Spot Size} \le 13\ \mu\text{m}$.

Selecting the middle of the acceptable range,

Scan Spot Size $\simeq 11\ \mu\text{m}$.

It is important to recognize that scanning with a pixel size of 11 μm will nearly preserve the original 39 ℓp/mm resolution, which should be attainable in the NAPP photograph using the new technology cameras. The number of 11 μm pixels in one 230- by 230-mm NAPP photograph is 432×10^6 pixels.

Clearly, one NAPP photograph from a new technology camera is a very dense storage medium. At this stage, the film image (analog) has been converted to digital pixels ready for digital photogrammetric applications. The cost to scan is estimated at $60 to $100 per frame for black-and-white or color scans.

Solid-State Digital Sensors

Digital sensors are generally mechanical scanners or electro-optical pushbroom sensors. Mechanical scanners have been used in the Landsat imaging sensors, but the future appears to be in electro-optical sensor arrays for scanning one line or an area at a time. The line scanners are referred to as linear arrays. Also, there are rectangular (area) arrays, referred to as

TABLE 2. TYPICAL MONOCHROME CCD ARRAY SPECIFICATIONS (COURTESY OF MANUFACTURERS)

Manufacturer	Detector Size (μm)	No. of Detectors	Array Data Rate (MHz)
Linear arrays			
Dalsa	10	6,000	60
Loral Fairchild	10	6,000	5
Kodak	7	5,000	25
EG&G Reticon	7	8,000	80
Time delayed integration (TDI) arrays			
Dalsa	13	32 × 6,032	110
Loral Fairchild	15	128 × 1,024	—
Kodak	—	Proprietary	—
EG&G Reticon	13	96 × 2,048	80
Staring (area) arrays			
Dalsa	12	5,120 × 5,120	60
Loral Fairchild	7.5	4,096 × 4,096	—
Kodak	9	2,048 × 2,048	20
EG&G Reticon	13.5	2,048 × 2,048	4

staring arrays, that image an area as opposed to a line at a time. See Tables 2 and 3 for typical arrays commercially available. Airborne reconnaissance systems have relied extensively on line scan and time delay and integration (TDI) arrays since the invention of CCDs in the 1970s (Boyle and Smith, 1970). TDI arrays enhance image content by integrating the radiometric values from more than one detector as they pass over the scene. Systems that use CCD focal plane arrays are known to have certain performance advantages over photographic film-based systems. The most significant benefit is the higher signal-to-noise ratio achievable under conditions of low scene contrast. This, in effect, takes the low-contrast Earth scene and performs a contrast stretch to enhance the content and interpretability of the image. Further advantages, particularly to the military, are that CCD-based arrays are amenable to real-time data transmission (Strunk and others, 1992). This is critically important to military reconnaissance, but not necessarily to civil mapping applications. Linear arrays and TDI arrays have been selected over area (staring) arrays largely because of their ability to provide suitable performance with faster readout rates and reasonable reconstruction of the image on the ground. Systems that employ linear array technology generally employ pushbroon scanning for image capture.

In the pushbroom scan mode, the line array of detectors is oriented perpendicular to the flight path of the aircraft-based sensor. A continuous succession of one-dimensional images are electronically sampled in such a way that the entire line array is read out in the time that it takes to advance the aircraft one pixel. Later, the pixels are reconstructed into the two-dimensional aerial image, which can be used in digital photogrammetry or printed on film for interpretation. Figure 1 illustrates the geometry of the pushbroom scanner. Line scanning works best with a predictable and stable flight pattern. Severe image reconstruction problems occur under turbulent flying conditions where roll, pitch, and yaw are unstable. Thompson (1979) pointed out that the advantages of line arrays include precise geometric positioning of the detectors, very high sensitivity with lightweight optics, low power consumption, and no moving parts. Further, radiometric calibration of thousands of detectors is feasible, and multiple array lines (chips) can be butted together to form thousands of detector elements in the line.

Compared with film cameras, Hartl (1989) stated that linear arrays have the advantages of better radiometric quality, wider spectral range, and direct delivery of digital information. The question is: How long will it take for the transition to this technology? It is well known that linear arrays are ideal for space altitudes where the space sensor platform is much more stable than in an aircraft. In an aircraft where the air is more turbulent and aircraft velocity is variable, there are some critical disadvantages that will challenge airborne sensor builders for a few years. Hartl (1989) pointed out that only the across-track line has geometric rigidity. Along-track imaging performance varies with the forward velocity and angular stability of the aircraft. This means that each scan line is not necessarily a continuous homogeneous image unit such as that attained with the aerial film camera. Any undetermined attitude or position variation from line to line greatly reduces the geometric fidelity of the pixel lines that form the image. In the worst case, this can lead to an interchange of two adjacent lines in the image when compared with the real ground scene.

For example, for NAPP photographs taken at an altitude of 6,000 m and 1-m ground resolution per line pair, a significant variation in aircraft attitude would lead to image overlap and crossover problems. The sampling frequency should be at least 2.2 times the maximum input frequency, as is generally accepted in commercial systems (Davies, 1991). This advocates that a reasonable and acceptable optical line pair-to-pixel relationship is 1 optical line pair equals 2.2 pixels. For a NAPP optical photograph with 1-m ground resolution to equal a scanning digital sensor, the pixel size in ground units should be 1 m ÷ 2.2 = 0.45 m. A ground pixel size of 0.45 m is 11 μm in the pixel plane. Then, if 20 percent (0.1 m) pixel overlap can be tolerated, the resulting angle of tolerance would be 3 arc seconds. Although 3 arc seconds of aircraft attitude variation is small, the overlap resulting from a greater variation would not be desirable. This suggests that FMC and AMC systems for digital sensors may be needed also.

Again, the homogeneous unit inherent in the optical photograph is a challenge to match. Based on this simple analysis, it can be concluded that attitude sensors must be capable of measuring as accurately as 3 arc seconds or better for each scan line of digital pixels, or, at the very least, the attitude model must recover attitude to this accuracy. Aircraft attitude sensors and stabilizing platforms are expensive, but such accuracy is essential to imaging success with pushbroom scanners. Also, any position error of the sensor, as determined from the global positioning system (GPS) or other positioning system, corresponds directly to an uncertainty of the pixel's image coordinate. If one needs to locate the pixel position to an accuracy of 0.1 m, then for an aircraft traveling at 270 knots (140 m/sec), the precise time allocation must be approximately accurate to 0.001 sec. Space platforms, being more stable in orientation and velocity, are more amenable to pushbroom technology. Even if these accuracies are attainable, the high data rates remain a formidable challenge for practical applications. Appendix B develops the data rate (60 Mb/sec) for the typical digital sensor NAPP mission. This 60-Mb/sec data rate is feasible, but is expensive in data transmission and storage capacity. On the other hand, long-term storage requirements for digitized photographs can also be expensive.

Stereomapping

Stereomapping by means of conventional frame-film cameras is well known, but using digital sensors for stereo acquisition

TABLE 3. TYPICAL THREE-COLOR LINE-SCAN CCD ARRAY SPECIFICATIONS

Manufacturer	Detector Size (μm)	No. of Detectors	Sensor Rate (MHz)
EG&G Reticon	13	4,096 × 3	20
Kodak	9	8,000 × 3	10

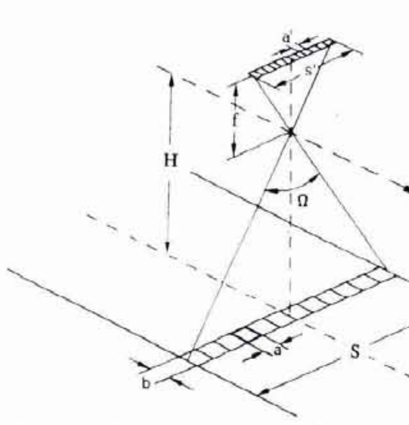

Figure 1. Geometry of a pushbroom scanner, where *f* is the focal length of the lens, *s'* is the length of the detector array, *a'* is the size of a detector element, *H* is the flying height above ground, *S* is the width of the array scan on the ground, *Ω* is the angular field of view, *a* is the width of one detector on the ground, and *b* is the length of one detector scan on the ground.

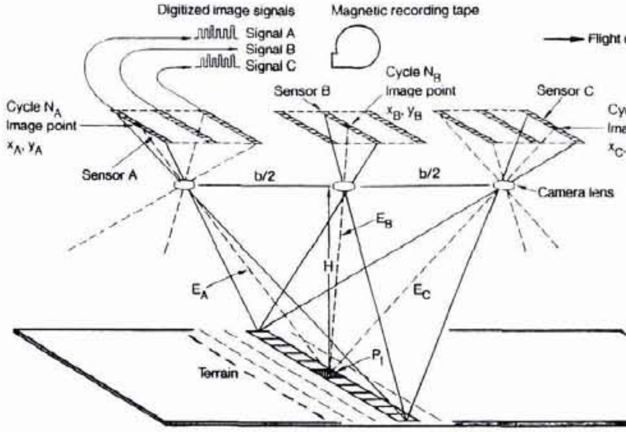

Figure 2. Digital sensing with a three-line-array camera (adapted from Hofmann and Náve (1984)).

is more complicated, particularly in an aircraft. Traditional mapping organizations are not yet set up to handle all-digital technology. For accurate stereomapping, the imager must view the same ground area from two different positions. And the ratio of the base between exposures to the height must be between 0.6 and 1 to achieve acceptable elevation accuracy. This can be achieved in space by viewing between (across) adjacent orbit tracks or with two convergent sensors in track—one looking forward and the second looking aft at the same ground scene. SPOT 1, 2, and 3 use the across-orbit technique. SPOT 5 plans to change to sensing stereo in-track by the turn of the century. The Japanese JERS-1 satellite employs arrays and achieves stereo in-track. Again, these configurations are useful for space systems, but are not entirely useful for the less stable aircraft platform.

One very interesting approach for using stereo pushbroom scanners is the German Modular Opto-Electrical Multispectral Scanner (MOMS) (Hartl, 1989; Ebner *et al.*, 1988; Ackerman *et al.*, 1990).

Stereo Digital Photogrammetry Using Linear Arrays

The MOMS concept, and the Digital Photogrammetric System concept of Hofmann and Nave (1984), shown in Figure 2, used a camera with three linear arrays mounted with a forward-, backward-, and downward-looking arrays mounted in the sensor's focal plane. The three images are taken at the same time. The rigidity of the camera's focal plane, and all three arrays using one lens for the forward-, backward-, and downward-looking optical system, turns the sensor into a fully digital system, although it still has sensitive attitude problems as in all linear arrays. Again, the forward motion of the aircraft records the three continuous lines of pixels and reads them out as each line is sampled by the array. Further experiments using the MOMS concept in aircraft could provide information to support the quest for all digital sensors. The MOMS concept, to some extent, minimizes attitude and crossover problems, but the data rate problem of handling massive amounts of pixels remains. The MOMS data rate is three times greater than a single pushbroom scan, but it is digital stereo data.

Staring Arrays

Staring (area) arrays, at first glance, are the most interesting, probably because they are basically a digital analog to a frame-film camera. Indeed, it would be ideal to have a staring array with enough detectors to be equivalent to the 230-by 230-mm format, which is the size of film in a frame camera. Using the NAPP as an example, it takes a pixel size of 11 by 11 μm to equal NAPP 1-m per line pair ground resolution. There are approximately 432×10^6 pixels per frame, so the array size would need to be 20,782 by 20,782 detectors.

As shown in Table 2, available staring array sizes are more like 5,120 by 5,120 detectors. Jenkins (1994) has pointed out that these arrays will rival film-based 35-mm cameras, but they are still four times too small in each direction to challenge the aerial frame-film camera. Butting several of these together could introduce small discontinuities between the rectangles that must be minimized if staring arrays are to be effective. Perhaps in the future, photogrammetric block adjustments could mathematically knit the array data together to form a scene unit, but the author is not aware of any reported experiments that are competitive with the 230-mm film width. Benkelman and Behrendt (1993) developed a system using 739 by 478 detectors that has the potential to grow to 1,024 by 1,024 detectors. Strunk *et al.* (1992) reported success with the 2,048 by 2,048 array (12-μm square pixels) for aerial reconnaissance. At the NAPP altitude, this sensor could achieve 1-m ground resolution, but the scene size would be only 2,048 by 2,048 m which is 1.27 by 1.27 miles (2.04 by 2.04 km) on a side. Current NAPP film covers 5.68 by 5.68 miles (9.14 by 9.14 km) on a side. It is obvious that far too many flight lines would be required to be economically competitive with the NAPP, so the challenge is to enlarge staring arrays and speed up their integration time and readout rates so that they can compete with 230-mm film sizes. If and when such technology becomes available, and as storage costs continue to decrease, the move to staring arrays will be very rapid.

Comparison of Digital Sensors and Film Cameras

Strunk *et al.* (1992) pointed out that high-speed, high-resolution CCD image sensors are suitable for airborne reconnaissance applications, but have mainly consisted of linear and TDI arrays. Staring arrays of 2,048 by 2,048 pixels have been developed for research, but this is too small for NAPP-like imaging. A study done at Fairchild Defense by James (1992) pointed out some of the tradeoffs between digital electro-optical (EO) and film sensors. These tradeoffs and others follow.

Positive Attributes of EO Systems

- State-of-the-art sensors, processors, and recorders.
- Low light level sensitivity due to ease of digital contrast enhancement.
- Few moving parts—low maintenance.
- Capability for electronic image enhancement and geometrical warping.
- Reusability of recording media.
- Cockpit display of targets to verify acquisition.
- Ability to datalink images as they are being collected.
- Ease of electronic transfer and encryption.

Drawbacks of EO Systems

- Sensors, processors, ground stations, and data compression are emerging technologies.
- High data rates are required to approach film resolution.
- Bit rate limitations exist for tape recorders.
- Attitude sensors are expensive.
- Mature standards do not exist for data transmission.
- Competitive standardized systems to drive performance up and costs down are not available.

Positive Attributes of Film Systems

- Mature technology: FMC and AMC cameras are internationally available.
- Very high resolution, large area coverage film is one homogeneous unit constituting inexpensive storage.
- Processing, exploitation, and dissemination expertise in place worldwide.
- Established reliability of performance.
- Many camera systems available worldwide.
- Sophisticated annotation and control systems in place.
- GPS-compatible.
- Excellent existing calibration and logistics support worldwide.

Drawbacks of Film Systems

- Processing takes time, clean water, and chemicals and produces hard copy not ready for electronic manipulation.
- Processed film must be scanned before it is computer ready, risking scratches on the film original.
- No direct means of confirming that target being photographed is available.
- Use is limited to available film emulsions and spectral characteristics.

Conclusion

The lack of quality large format digital cameras is a major impediment to digital image photogrammetry at this time. Modern aerial film cameras with FMC and AMC can provide resolution up to approximately 54 ℓp/mm to the film user on high-contrast targets and 39 ℓp/mm on low-contrast scenes. CCD cameras are mounting a challenge, but it is easy to agree with Torlegard (1992) that the aerial camera will be the main sensing system for map production and revision in large- and medium-scale cartography for the next several years. These reasons support using film cameras for the NAPP for the next several years.

Aerial photographs will remain a primary source of data as the integration of DEMs, orthophotos, and GISs continues. The digital photogrammetric workstation will serve as a tool in this process, and digital scanning of photographs (film) will be standard in larger photogrammetric production units. This is ideal for a technology in transition. By the time quality and cost-effective digital sensors are available to replace the aerial film camera, the digital technology to accept the digital pixels will already be in place. In the meantime, much research is needed to provide a smooth, but probably inevitable, transition to an all digital environment. In fact, high-resolution space systems are also contenders to be the sensor for the future, particularly where large area coverage is required, such as in the NAPP.

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Appendix A
Image Quality as a Function of Lens, Film, Forward Motion, and Angular Motion

Effects of Image Motion Due to Aircraft Velocity (Forward Motion)

The amount of image movement or blur (b) due to the velocity of the aircraft is given as follows:

$$b = f \times \frac{V}{H} \times t \tag{A1}$$

where f is the focal length of the camera, V is the velocity of the aircraft, H is the flying height above terrain, and t is the shutter speed-time duration of the photographic exposure.

Using Equation A1 for a typical NAPP mission, with V = 270 knots, H = 6,096 m (20,000 ft), f = 152 mm, and the shutter speed is 1/300 second, the image blur due to forward motion is only 12 μm.

Effects of Angular Motion on the *xy* Coordinates of a NAPP Photograph

The effects of angular motion due to changes over time of roll ($\dot{\omega}$), pitch ($\dot{\varphi}$), and yaw ($\dot{\kappa}$) of the aircraft smears the xy coordinates, causing image blur, which effects the resolution of the photograph. To estimate this effect, a typical NAPP flight with

$\dot{\omega} = \dot{\varphi} = 1°/\text{sec} = 0.0174533$ radians/sec
$\dot{\kappa} = 0.5°/\text{sec} = 0.0087266$ radians/sec
x = 115 mm (maximum photo coordinate in flight direction)
y = 115 mm (maximum photo coordinate perpendicular to flight direction)
t = 1/300 sec

Table A1 using the above parameters shows the image blur at the edge of the photograph due to angular motion for a typical NAPP mission.

The six individual blur values from Table A1 should not be added because the probability of each source contributing its value at the same time is very remote. Therefore, the root-sum-square of the six values yields the blur distance based on the same probability of occurrence (Kawachi, 1965). Therefore, the image blur (b_{AM}) for a typical NAPP photograph taken with state-of-the-art cameras would be as follows:

$$b_{AM} = (5^2 + 14^2 + 14^2 + 5^2 + 3^2 + 3^2)^{1/2} = 21\ \mu m = 48\ \ell p/mm.$$

Notice that b_{AM} is larger than the 12 μm computed for b_{FM} = 12 μm = 83 ℓp/mm.

System Resolution (Rs)

The combined influence of the lens, the original and duplicate films, the forward motion (FM), and the angular motion (AM) on the total system resolution can be approximated by the following formula (Meier, 1984; Kawachi, 1965):

$$\frac{1}{R_s^2} = \frac{1}{R_L^2} + \frac{1}{R_f^2} + \frac{1}{R_{FM}^2} + \frac{1}{R_{AM}^2} + \frac{1}{R_D^2} + \ldots \tag{A2}$$

where

R_s	is total system resolution in line pairs per mm (ℓp/mm),
R_L	is the area weighted average resolution (AWAR) of the camera lens - laboratory calibration (95 ℓp/mm),
R_f	is the resolution of the taking film (130 or 55 ℓp/mm, depending on contrast),
R_{FM}	is the forward motion blur converted to ℓp/mm (83 ℓp/mm),
R_{AM}	is the angular motion blur converted to ℓp/mm (48 ℓp/mm), and
R_D	is the resolution of the duplicating film (100 ℓp/mm).

Table A1. Coordinate Movement Due to Angular Motion

Motion Item	Angular Motion Equation	xy Coordinate Movement for 1/300 Seconds (μm)
Roll ($\dot{\omega}$)	$\dot{x}_\omega = \frac{xy}{f}\dot{\omega}$	5
	$\dot{y}_\omega = \left(\frac{f^2 + y^2}{f}\right)\dot{\omega}$	14
Pitch ($\dot{\varphi}$)	$\dot{x}_\varphi = \left(\frac{f^2 + x^2}{f}\right)\dot{\varphi}$	14
	$\dot{y}_\varphi = \frac{xy}{f}\dot{\varphi}$	5
Yaw ($\dot{\kappa}$)	$\dot{x}_\kappa = y\dot{\kappa}$	3
	$\dot{y}_\kappa = x\dot{\kappa}$	3

Table A2. System Resolution

System Resolution	Camera AWAR (ℓp/mm)	Camera Film		Duplicate film (ℓp/mm)	Motion	
		1000:1	1.6:1		FM 12 μm	AM 21 μm
R_s (ℓp/mm)	95	130	55	100	83	48
49	X	X	—	X	X	—
38	X	X	—	X	—	X
60*	X	X	—	X	—	—
34	X	X	—	X	X	X
38	X	—	X	X	X	—
24	X	—	X	X	—	X
43*	X	—	X	X	—	—
30	X	—	X	X	X	X

Table A2 contains the system resolutions that can be expected from the new cameras considering the components defined in Equation A2. Values are calculated with Equation A2 for various combinations expressed in ℓp/mm in the image plane. When an X appears in Table A2, the value above it is used in Equation A2 to estimate the system resolution, which may be 90-percent attainable in the actual aerial case.

The data in Table A2 show that blur caused by forward and angular motion can be the weakest link in the imaging chain and that the resulting system resolution on the film can be improved with FMC and AMC. In practice, however, it is generally not beneficial to correct for FMC when using 6-inch focal length cameras at flying heights above 15,000 feet.

Because of variations in velocity, elevation, and a variety of atmospheric conditions, it is not practical to expect to compensate 100 percent for all motions and to have all high-contrast ground scenes that could yield 60 ℓp/mm as shown on the third line of Table A2. In fact, the Earth is, in general, a low contrast 1.6:1 scene. So, accepting that 90 percent of the 43 ℓp/mm and 60 ℓp/mm as shown on the third and seventh line of Table A2 can be attainable, it is reasonable to expect in practice that approximately 0.9×43 ℓp/mm $\cong 39$ ℓp/mm and 0.9 x 60 ℓp/mm $\cong$ 54 ℓp/mm is possible with today's aerial cameras that have both FMC and AMC to minimize motion effects on resolution.

Appendix B

Data Rate for a Pushbroom Sensor: A NAPP Example

Using the pushbroom geometry as shown in Figure 1, and assuming the same basic parameters as for NAPP photographs, the calculations for data rate are as follows:

$$\text{Line Rate} = \left[\frac{\text{Aircraft Velocity (m/sec)}}{H\ \text{(m)}}\right] \times \frac{\text{focal length (mm)}}{\text{pixel width (mm)}} \times \sin^2 \text{(depression angle)}.$$

For NAPP type imaging, the parameters are Velocity = 270 knots (138.9 m/sec), H = Altitude of 20,000 ft (6,096 m), Focal length = 152 mm, Pixel width = 0.011 mm in the image plane, and Depression angle = 90° (vertical).

Therefore,

$$\text{Line Rate} = \left[\frac{138.9\ \text{m/sec}}{6{,}096\ \text{m}}\right] \times \frac{152\ \text{mm}}{0.011\ \text{mm}} \sin^2 90^\circ$$

$$= 355\ \text{lines/sec.}$$

Data Rate

For a NAPP-like digital image, the number of 11- by 11-μm pixels across track are 20,782 pixels/line. Then,

$$\text{Pixel rate} = 20{,}782\ \text{pixels/line} \times 355\ \text{lines/sec} = 7{,}377{,}500\ \text{pixels/sec.}$$

Considering 8 bits/pixel for panchromatic images, the final NAPP-like data rate in bits/sec is 59,020,880 bits/sec, or approximately 60 Mb/sec.

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4. Analytic Data-Reduction Schemes in Non-Topographic Photogrammetry
5. Camera Calibration in Non-Topographic Photogrammetry
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