Digitizing Aerial Photography - Understanding Spatial Resolution

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Abstract

Accuracy, flexibility, and cost effectiveness are advantages of using digitized aerial photographs as a data source. However, the relationship between the resolution of digital images, and the aerial photographs from which they were derived, must be addressed.

In the following paper we consider issues that impact the spatial resolution of photographs and digitized images, and suggest how users can optimize spatial resolution by selecting an appropriate scanning aperture. Optimal scanning aperture can be chosen by considering the camera system resolution, the original photograph's scale, and the desired pixel size of the digital image.

There are optimal scanning resolutions to use when digitizing aerial photographs. Optimizing spatial resolution will maximize the spatial information obtained from the original photographs without generating unnecessarily large file sizes.

Introduction

Digitized aerial photography is increasingly being used as a data source for studying and managing environmental elements such as trees (Niemann et al., 1999) and forests (Leckie et al., 1999; Niemann et al., 1999). The popularity of digitizing aerial photography is a result of the advantages of working with digitally formatted data (Warner et al., 1996). For example, digital imagery can be manipulated with relative ease allowing for atmospheric and geometric corrections, image enhancements, data compression, and viewing options (Lillesand and Kiefer, 1994). As well, digital images provide potential for semi-automated image analysis (Barbezat and Jacot, 1999; Gougeon, 1999). One disadvantage of converting photographs into digital imagery is that spatial resolution is reduced during the digitizing process (Warner et al., 1996).

Spatial resolution is one factor which governs the information content of an image. Digitizing photography with the smallest available scanning aperture reduces loss of spatial resolution, however such an approach produces file sizes which are unnecessarily large and unwieldy to use. In this paper we suggest techniques to optimize, rather than maximize, the scanning aperture, thereby allowing important image information to be retained and file sizes to be minimized. Choice of scanning aperture is related to the resolution of the original photograph and/or the desired pixel size of the digital image.

Although in this paper we only consider the affect of scanning aperture on spatial resolution, it is recognized there are other impacting factors. For example, systematic errors resulting from shifts in the position of points within the pixel pattern reduces spatial resolution (Trinder, 1987). As well, fitting homogenous square pixels to landscapes which are heterogeneous in shape and size will adversely affect spatial resolution (Fisher, 1997). Target and film contrast also affect the resolution of imagery; the higher the contrast the better the potential to resolve unique features (Avery and Berlin, 1992). Additionally, scanner and input image quality impact the spatial resolution of digitized imagery. Although we do not discuss it is in this paper, it should be noted that other types of resolution such as reflectance and colour affect the usability of digital imagery.

Depending on the anticipated use of digital imagery, different approaches should be used to

determine the scanning aperture required to optimize spatial resolution. If digital imagery is to be used for visual interpretation, a visual comparison of images scanned with varying sized apertures should be made. The largest scanning aperture which provides all required information is best used to minimize file size. Recent operational work by British Columbia's Ministry of Environment Lands and Parks (MELP) suggest that when producing digital imagery for visual interpretation, a scanning aperture between 10-14 microns will optimize the spatial resolution when digitizing film; and a scanning aperture of 36 microns is optimal when digitizing prints (Fish, 2000).

Not all digital imagery is used for visual interpretation. Often it is used as input for image processing. Particularly when imagery is used with semi-automated techniques, visual interpretability becomes secondary to maintaining the digital information required for processing. *In this paper our goal is to present methods for selecting a scanning aperture which will optimize spatial resolution when converting aerial photography film into digital imagery that is to be used for image processing.* In the following paper we define spatial resolution, present methods for optimizing spatial resolution, and discuss example results of the spatial resolution optimization techniques used when scanning aerial photographs.

Spatial Resolution

Aerial Photography and Spatial Resolution

Camera System Resolution

There are many ways to define the spatial resolution of a photograph or digital image. Table 1 is a summary of the spatial resolution measurements discussed in this paper. The spatial resolution of aerial photography is defined as the capability of a camera system to image spatial detail (Avery and Berlin, 1992). In this paper we use Avery and Berlin's (1992) definition of spatial resolution to define *camera system resolution* which is measured using a tri-bar resolution test chart (Figure 1). The tri-bar chart consists of consecutively smaller groups of three parallel lines separated by spaces equal to the width of the lines (Lillesand and Kiefer, 1994). The size of the smallest lines distinguishable on the film is the resolution of the camera system (expressed in line pairs per millimetre).

Camera lens and film are the key components which affect camera system resolution. The speed of a lens, or aperture setting, controls the amount of light available at the film's surface. As the aperture opens to increase light at the film's surface, image sharpness decreases and vice versa. Therefore, the aperture setting is a compromise between image sharpness and the amount of light required for exposure.

The film's emulsion is composed of silver halide grains, the size of which affects the amount of light required to expose the film and the graininess of the image. As silver halide grains decrease in size image resolution improves, but more light is required for exposure. Resolution may be sacrificed in order to achieve appropriate exposures (Avery and Berlin, 1992).

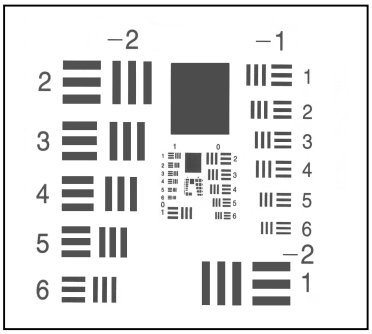

Figure 1. *Tri-bar resolution test chart (Avery and Berlin, 1992).*

Measurements of camera system resolution do not take into account the effects of converting the image from a negative to photographic paper. Generally, the spatial resolution is decreased during printing as the emulsion of the photographic paper has a lower spatial resolution than the emulsion of the film. Therefore, the camera system resolution is only an accurate measure of the film, not the print, resolution.

Table 1. *Summary of the resolution measurements discussed in this paper. Adjacent resolution definitions for aerial photography and digital imagery are comparable. For example, the closest digital resolution measurement to camera system resolution is scanning aperture.*

Aerial Photography			***Digital Imagery***		
Resolution	**Definition**	**Units**	**Resolution**	**Definition**	**Units**
Camera System Resolution	The capability of the camera and film system to image spatial detail (Avery and Berlin, 1992).	line pairs per mm	**Scanning Aperture**	The pixel size used to sample an image during digitizing. As the size of the scanning aperture decreases the spatial resolution theoretically increases.	microns
Ground Resolution	The number of line pairs which represent 1 m on the ground (Avery and Berlin, 1992).	line pairs per m			
Minimum Detectable Object Size (MDOS)	The size of the smallest object which can be detected. MDOS is equivalent to the ground distance represented by one line of a line per mm pair (Avery and Berlin, 1992).	cm or m	**Pixel Size**	The ground area represented by a specific size of scanning aperture, when used in conjunction with a certain scale of imagery.	cm or m
Effective Resolution	The smallest object that can be separated from the background. Similar to MDOS, but also considers the effects of contrast, atmosphere, etc, (Hyppanen, 1996).	cm or m	**Effective Resolution**	The smallest object that can be separated from the background. Similar to pixel size, but also considers the effects of contrast, atmosphere, etc. (Hyppanen, 1996).	cm or m

Ground Resolution

Ground resolution considers the effect of scale and camera system resolution on the ability to identify ground objects (Avery and Berlin, 1992). Ground resolution is equivalent to the number of line pairs it takes to represent one metre on the ground and is calculated with the following equation:

$$Rg = \frac{(Rs)(F)}{H} \qquad (1)$$

where: Rg = ground resolution in line pairs per metre

R_s = camera system resolution in line pairs per millimetre

F = focal length in millimetre

H = height of camera above ground in metres

Photographic scale is a ratio of the focal length and height of the camera above ground, therefore ground resolution is a function of photographic scale and camera system resolution. As the photographic scale and the camera system resolution decreases, the ground resolution also decreases.

Minimum Detectable Object Size

Once the ground resolution is calculated, the *minimum detectable object size* (MDOS) can be determined. The MDOS is the equivalent to the ground distance represented by one line of a line per millimetre pair as measured by the tri-bar chart (Avery and Berlin, 1992). To determine the MDOS first calculate the ground resolution, then determine the ground distance represented by a single line pair using the following equation:

$$width\ of\ a\ line\ pair\ in\ meters = \frac{1\ line\ pair}{Rg} \qquad (2)$$

The MDOS is the ground distance represented by one line. To calculate:

$$MDOS = width\ of\ one\ line\ in\ meters = \frac{width\ of\ a\ line\ pair\ in\ meters}{2} \qquad (3)$$

The width of one line in a line per millimetre pair is the equivalent to the MDOS. Theoretically, all objects equal in size to the MDOS can be identified. The MDOS is a hypothetical measure of spatial resolution (Rosenburg, 1971) and assumes that an object of size equal to the MDOS is fully recorded by a single silver halide grain. This is unlikely as generally several grains record a portion of an object and are used in conjunction with one another to identify an object. Although the MDOS is a useful rule of thumb, it should be remembered that in practical terms the actual MDOS is likely smaller than reported.

Digital Imagery and Spatial Resolution

Scanning Aperture

The resolution of a digital image, generated via the scanning of an aerial photograph, is based on the *scanning aperture* (measured in microns) is used for digitizing. The scanning aperture is the size of the pixel used to sample an image. For example, an image digitized with a scanning aperture of 14 microns is sampled at a rate of 714 pixels per centimetre. As the size of the scanning aperture decreases the sampling rate increases, theoretically improving spatial resolution. Although dots per inch (dpi) is a term meant to express printer resolution, it is commonly used to describe the sampling rate. To convert scanning aperture in microns to dpi use the following equation:

$$dpi = \frac{25400}{\mu m} \qquad (4)$$

where μm = scanning aperture in microns

Theoretically, if an image being scanned has infinite resolution and the scanner is perfectly engineered the scanning aperture is a measure of the digital image resolution. Although for most practical purposes the film's spatial resolution is infinite (as it is almost always higher than the spatial resolution available from even the scanner's smallest aperture setting), scanning errors should be expected to reduce spatial resolution. Also, prints have a much lower spatial resolution than film and limit the potential spatial resolution of digital images.

Pixel Size

Pixel size is the most common way to report the resolution of digital imagery and is approximately equivalent to the MDOS. For example, if a digital image has a pixel size equal to one metre, then the MDOS can be no greater than one metre. The pixel size of a digital image is based on the scanning aperture and the scale of the original imagery, and is calculated with the following equation:

$$p = s \times \frac{\mu m}{1{,}000{,}000} \qquad (5)$$

where: p = pixel size in metres
s = scale of imagery

Therefore, pixel size is the ground area represented by a scanning aperture when used in conjunction with a specific scale of imagery.

Effective Resolution

The *effective spatial resolution* describes what can actually be discerned on an image once factors such as target contrast, atmospheric condition, noise, and resampling have been accounted for (Hyppanen, 1996). The concept of effective resolution can be applied to both photographs and digital imagery, however generally refers to the latter. Although the spatial resolution of a digital image can never be greater than the pixel size it is often possible to identify high contrast features at a sub-pixel level. For example, when working using imagery with a spatial resolution of 30 metres, roads, passing through forest, which are less than 30 metres wide are often visible due to their high contrast.

Methods for Optimizing the Spatial Resolution of Digital Imagery

Following is a discussion of two methods for optimizing the spatial resolution of a digital image during scanning. Both methods require diapositives or film for input, and produce digital data for image processing. As well, both methods are based on controlling spatial resolution by selecting an appropriate scanning aperture. The first optimization method is based on maintaining the camera system resolution and the MDOS; the second method is based on generating a digital image with a pixel size

which optimizes the variance around an object of interest.

Calculating Scanning Aperture Based on Camera System Resolution and MDOS

The aperture used for scanning may be selected so that the scanner system resolution equals that of the camera system. Sampling theories, such as the Kell factor, suggest that to maintain spatial resolution the scanning aperture must be set at 2.5 to 3 times the original resolution (Konecny et al., 1979). Sampling at a higher resolution than provided by the original image is required to reduce systematic errors caused when the scanner signal does not line up precisely with the grains of the film. Choosing a scanning aperture with a 1:1 ratio could result in the loss of information if the sample is always taken at the bridge between two film grains. Therefore, if maintaining the information of every silver halide particle of the photograph is important the Kell factor should be implemented. However, in many circumstances this level of accuracy is not required as the information available from the photograph is greater than required for image analysis. Also, the large file sizes produced by applying the Kell factor when scanning may prohibit certain types of analysis.

The camera system resolution is reported in lines pairs per millimetre, whereas scanner resolution is reported in microns. By converting microns to pixels per millimetre, and line pairs per millimetre into lines per millimetre, the resolution of the camera system and scanner can be compared. In Figure 2 we present a comparison between the camera system resolution measured in lines per millimetre and the associated scanning aperture in microns. The scanning aperture required to maintain both the camera system resolution using a 1:1 ratio and the 1:2.5 ratio of the Kell factor are shown. Based on a hypothetical camera system resolution of 25 line pairs per millimetre, we demonstrate that to maintain a camera system resolution with a 1:1 ratio a scanning aperture of 19.5 microns is sufficient (Figure 2). However, if the Kell factor must be implemented a scanning aperture of 7.94 should be used.

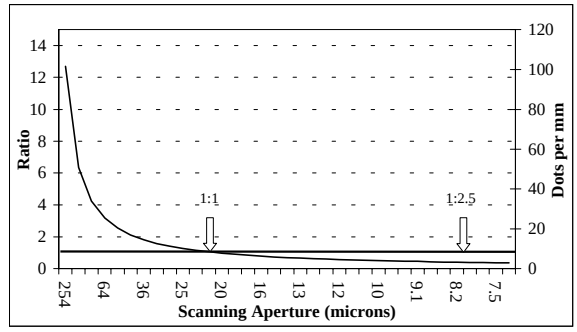

***Figure 2**. A comparison of scanning aperture and line pairs per metre. If scanning at a 1:1 ratio an aperture of 19.5 microns should be used; if implementing the Kell, factor, which has a ratio of 1:2.5, a scanning aperture of 7.95 microns should be used.*

Calculations for the MDOS are based on a resolution equal to the camera system resolution. This means that to maintain the MDOS an image must be scanned using the same aperture as required to maintain the camera system resolution. The MDOS is a measure of the maximum amount of information available from an image, therefore it makes sense that to maintain the MDOS all the original information must be retained.

Calculating the MDOS will not change the choice of scanning aperture; however, knowledge of the MDOS may be important to determine if an image provides enough information to study a particular size of object. For example, if the camera system resolution is 50 line pairs per metre, the focal length of the lens is 300 millimetres, and the aircraft flying height is 5000 metres, the ground resolution will equal three line pairs per metre. Therefore, one line pair equals 0.33 metres on the ground and one line equals 0.17 metres on the ground. The MDOS is 0.17 metres therefore, no object less than 0.17 metres in size can be studied with this imagery.

Calculating Scanning Aperture Based on Size of Objects of Interest

Another way to determine the appropriate scanning aperture is based on maximizing image variance at the edge of an object of interest. Selecting a scanning aperture which results in high variance around an object is beneficial as it improves the accuracy of semi-automated

feature extraction techniques. Preliminary results suggest that pixels 0.17 the size of the object of interest result in high variance at an object's boundary. Therefore, if the objects of interest are trees with crown diameters of four metres, a pixel size no larger than 0.68 metres is desirable. Although some trees with four metre crowns will be detected using a larger pixel size, the percentage of trees accurately located will decrease.

Once the appropriate pixel size has been determined, the scanning aperture can be calculated using the following equation:

$$\mu m = \frac{p}{s} \qquad (6)$$

The scanning aperture is a ratio of the scale of the original photograph and the desired pixel size.

Results of Optimizing the Spatial Resolution of Digital Imagery

In Table 2 we compare the scanning aperture suggested to maintain the camera system resolution using both a 1:1 ratio and the Kell factor ratio of 1:2.5. For all calculations in Table 2 the scale is 1:15000. In Table 2 we demonstrate why implementation of the Kell factor may be impractical. Even if one has access to a scanner capable of digitizing with very small scanning apertures, doing so will generate large file sizes. Although data storage capacity and retrieval speeds are constantly increasing, file sizes of this magnitude are often impractical. For example, generating an orthophoto requiring the use of several images having file sizes greater than a gigabyte will be difficult. Using large files, many processes could become onerous due to technical limitations and time constraints.

Another factor to consider when scanning aerial photography is that if the object of interest is smaller than the MDOS, the imagery cannot provide enough spatial detail to analyze the object. The information provided by the photograph is not sufficient to detect objects smaller than the MDOS. In Table 3 we demonstrate that when the object size of interest is 0.5 metres, the scanning aperture required to maximize the variance of the object size of interest is smaller than the scanning aperture required to maintain the MDOS. This suggests that objects 0.5 metres in size cannot be analyzed with this imagery.

In Table 3 we compare the scanning aperture size for maintaining camera resolution and for maximizing image variance for a particular object size. Unless the objects of interest are small, the size of the scanning aperture required to maximize pixel variance is larger than the scanning aperture required to maintain the camera system resolution and MDOS. When digitizing to optimize the variance of an object's edge, the appropriate scanning aperture can be selected without requiring camera calibration information, such as camera system resolution. This is useful as camera calibration information is not always available. It should be mentioned that optimizing the spatial resolution of a digital image based on maximizing the variance at an object's boundary is not always appropriate. For example, if an image is to be used by different users for a variety of purposes or if several objects of different size are being analyzed, it may not be appropriate to select a scanning aperture based on object edge variance.

Table 2. *Compares the dpi calculated to maintain the camera system resolution using a 1:1 ratio and the Kell factor of a 1:2.5 ratio. All image scales equal 1:15000.*

Camera System Resolution (line pairs/mm)	Scanning Aperture Required to Maintain Camera Resolution and MDOS with a 1:1 ratio (µm)	File Size for Aerial Photograph (scanned at a 1:1 ratio) 10 X 10 inches in megabytes	Scanning Aperture Required to Maintain Camera Resolution and MDOS with a 1:2.5 ratio (µm)	File Size for Aerial Photograph (scanned at a 1:2.5) ratio) 10 X 10 inches in megabytes
25	20.00	161	8.00	1008
50	10.00	645	4.00	4032
75	6.67	1452	2.67	9073
100	5.00	2581	2.00	16129

Table 3. Summary of optimal dpi suggestions. Note that the dpi based on maximum variances is calculated with a pixel size equal to 0.17 the size of the object of interest. All calculations are based on a 1:1 ratio. All image scales equal 1:15000 and 80 lppmm.

Scanning Aperture Required to Maintain the Minimum Detectable Object Size (µm)	Object of Interest Size (m)	Scanning Aperture Required to Maximize Image Variance Based on Object of Interest Size (µm)
6.25	0.5	5.56
6.25	1	11.11
6.25	1.5	16.67
6.25	2	22.22
6.25	3	33.33
6.25	4	44.44
6.25	5	55.56
6.25	6	66.67

Conclusions

Choosing an appropriate scanning aperture when digitizing aerial photography is a balancing act between information required and manageable file sizes. Following are a few rules which should guide the process of appropriate scanning aperture selection.

- It is best to optimize, rather than maximize, spatial resolution when generating a digital image from an aerial photograph.
- Regardless of the scanning aperture used, data can never be created.
- Use the Kell factor cautiously. For most general remote sensing applications the accuracy provided by the Kell factor is not required.
- Scanning an image with a smaller scanning aperture than is required to maintain the camera system resolution and MDOS, will theoretically improve the spatial resolution but no more useful information will be captured
- The scanning aperture suggested to maintain the camera system resolution and MDOS assumes the negative, not the print, is being scanned. If scanning a print, the spatial resolution will be reduced and a smaller scanning aperture should be used.
- Using a scanning aperture which maximizes variance at the edge of a certain size of object, will likely increase the aperture size required for scanning.
- If the objects of interest are smaller than the MDOS the data can not provide sufficient information for analysis.

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