Mapping Matters

By Qassim A. Abdullah, Ph.D., PLS, CP**

Your Questions Answered

The layman's perspective on technical theory and practical applications of mapping and GIS

We have started utilizing digital camera imagery taken by Intergraph DMC II 140 and Microsoft UltraCamX with GSD ranging from 5cm to 15cm to produce mapping products. On one set of imagery flown with DMC II 140 digital sensor with 14 cm GSD, the photo scale was reported to be 1:19,921 (when the mean terrain height for the project was 750 ft and the flight height was 6,800 ft ASL) as compared to a scale of 1:7,200 if I used a standard aerial film camera. Is there a reference chart or formula that will allow me to relate the GSD at a certain flight height to a film-based cameras photo scale? What would be the formula to compute the accuracies of the certain GSD for allowable contour interval generations to meet ASPRS Class 1 Accuracy Standards? We typically scan the film at 16 microns for mapping only projects and 12 microns for orthophoto/mapping projects. I realize that each of the digital sensors has unique parameters, so there may not be a global formula.

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Dr. Abdullah: Your question brings up a common concern among users of the new digital aerial sensors who are accustomed to the typical film camera specifications of 9-inch film format and a lens with 6-inch focal length. Aerial film cameras, which have dominated the aerial photography market for the last few decades, share the same design philosophy of the frame-based format with film size of 9x9 inches and a lens with focal length of 6 inches. This commonality in the film camera design made it easy for the mapping community to estimate and predict the accuracy of the products generated from these cameras. Since film camera formats are standard (fixed film size and lens), the scale of aerial imagery acquired by these metric cameras is influenced mainly by the flying altitude. Traditionally map scale is derived from the photo scale using an enlargement factor, also known as the "enlargement ratio". In addition, an enlargement ratio of 6 became the industry standard for film-based aerial photography. This value for the enlargement ratio was adapted during or after World War II to suit the quality of film and the plotting instruments used in paper map making at that time. Over the years, it has become a standard practice to acquire aerial imagery from an altitude of 3,600 ft (or 1,100m) AMT with a scale of 1"=600' (or 1:7,200) to produce maps with scale of 1"=100' (or 1:1,200) using the standard aerial metric film camera mentioned above and the popular enlargement ratio of 6. In fact, some agencies. such as the U.S. Army Corps of Engineers (COE). hard coded the relation between photo scale and map scale into their "Technical Engineering and Design Guides" which were later adopted by the American Society of Civil Engineers under the "Photogrammetric Mapping" manual. When softcopy photogrammetry was introduced in the early 1990s, scanning the film at a resolution of 1209 dpi (dots-per-inch) or 21um became the magic number as it resulted in a smaller file size. Scanning a film with a scale of 1"=600' (1:7,200) using 1209 dpi (21um) scanning resolution results in a digital scanned image with a Ground Sampling Distance (GSD) of 0.50 ft. A GSD of 0.50 ft is adopted to represent details presented in a map with a scale of scale of 1"=100' (1:1,200). In a similar fashion, a GSD of 1.0 ft represented a map with scale of 1"=200' (1:2,400) and so on. Since then, users tried to reap the fruits of technological advances in film manufacturing and map making processes that result in more accurate maps by stretching the limits governed by the flying altitude and the enlargement ratio. Map manufacturers found that scanning the film with finer resolutions such as 1814 dpi (14 um) or 3629 dpi (7 um) enabled them to acquire photography from higher altitudes while still providing the GSD required for the final mapping products.

> *"Some of the modern digital sensors are manufactured with lenses that have a longer focal length and smaller (CCD) size that allows users to fly higher while maintaining high image resolution of the ground"*

> *"This commonality in the film camera design made it easy for the mapping community to estimate and predict the accuracy of the products generated from these cameras."*

Before going further, I would like to clarify the previous discussion with a numerical example. For a film that was acquired from an altitude of 3,600 ft (or 1,100m) AMT and resulted in a film scale of 1"=600' (1:7,200), a scanning resolution of 1209 dpi or 21um is needed to produce a map with a GSD of 0.5 ft (15cm) and a scale of 1"=100' (1:1,200). The same GSD and map scale can also be obtained from a film acquired with a scale of 1"=1,200' (or 1:14,400) from an altitude of 7,200 ft (or 2,200m) if the film is scanned with twice the scanning resolution or 2,418 dpi or 10.5 um. However, the resulting enlargement ratio will be 12 instead of the standard figure of 6.

Table 1. Effect of scale and scanning resolution on GSD

Film scale: 1"=600' (or 1:7,200) Lens FL=6"(150mm)			
Flying Altitude: 3,600ft (or 1,100m) AMT Film: 9x9in.			
Scanning Resolution		X-ratio	Resulting GSD
um	dpi		
7	3,629	18	0.16' / 4.9 cm
14	1,814	9	0.33' / 0.10 m
21	1,209	6	0.50' / 0.15 m
28	907	4	0.66' / 0.20 m
56	454	2	1.32' / 0.40 m

Table 1 clearly demonstrates that scanning the film with 1,814 dpi or 14um resulted in a GSD of 0.33 ft, which can be translated into a 34% reduction in acquisition cost if the same project was flown from different altitude to results in the same GSD of 0.50 ft. Table 2 shows that one can obtain the same GSD from different flying altitudes and therefore different film scales if the film is scanned with different resolutions. In Table 2, an orthophoto with a scale of 1"=100' (1:1,200), or a GSD of 0.50 ft, can be obtained from the following three scenarios:

1) Flying altitude of 3,600 ft or film scale of 1"=600' (1:7,200) and scan resolution of 1209 dpi (21 um) resulting in an enlargement ratio of 6;
2) Flying altitude of 5,400 ft or film scale of 1"=900' (1:10,800) and scan resolution of 1,814 dpi (14 um) resulting in enlargement ration of 9;
3) Flying altitude of 10,800 ft or film scale of 1"=1,800ft (1:21,600) and scan resolution of 3,629 dpi (7 um) resulting in enlargement ratio of 18.

Table 2. Relationship between film scale, scanning resolution, and resulting GSD

Film scale 1"=ft	GSD (ft) @ xxx dpi		
	3,629	1,814	1,209
600	0.17	0.33	**0.50**
900	0.25	**0.50**	0.74
1,800	**0.50**	0.99	1.49

"it is not practical to use accuracy criteria that is mainly defined by flying altitude as is the case with film cameras, as manufacturers of digital sensors followed different design philosophies and produced digital sensors with different sensor (CCD array) size, Charge Coupled Device (CCD) size, and lenses focal lengths."

Scenario number 2 was widely practiced, while scenario number 3 is never utilized due to the following reasons:

1) **Degradation in Map Accuracy:** The flying altitude plays a critical role in determining the accuracy of the derived map as higher altitude exaggerates the effect of errors caused by inaccuracy in the sensor orientation angles. Therefore, it is only possible to stretch the flying altitude to a limit beyond which it becomes impossible to meet the accuracy for the intended map. That stretch-factor is not well defined but it is definitely a valid concept due to the advancements in the hardware of aerial sensors and the computational model which made it possible to achieve better accuracies using more efficient and economical acquisition parameters. Many users are finding that they can fly aerial sensors higher than the standard guidelines call for while still achieving the required accuracy. Although there are more sources of error that are considered in modeling the mapping process, the error in sensor orientation determination is considered the greatest contributor in determining the final map accuracy. In the past we believed that the photogrammetric-determined sensor orientation angles using aerial triangulation must be accurate to within 10 arcsec for the map to meet engineering grade map accuracy. This accuracy figure is based on an older generation of film, sensor, mapping instruments, and mathematical models. Better accuracy is expected now using more modern and more accurate processes and technologies. The following derivations demonstrate a high level model to study the effect of errors in the orientation angles on the final map positioning accuracy. I would like to start with the effect of errors in omega and phi (or roll and pitch) on the positional accuracy of a map. Figure 1, illustrates the relation between the orientation angles error in omega and phi and their effects on the map's coordinates.

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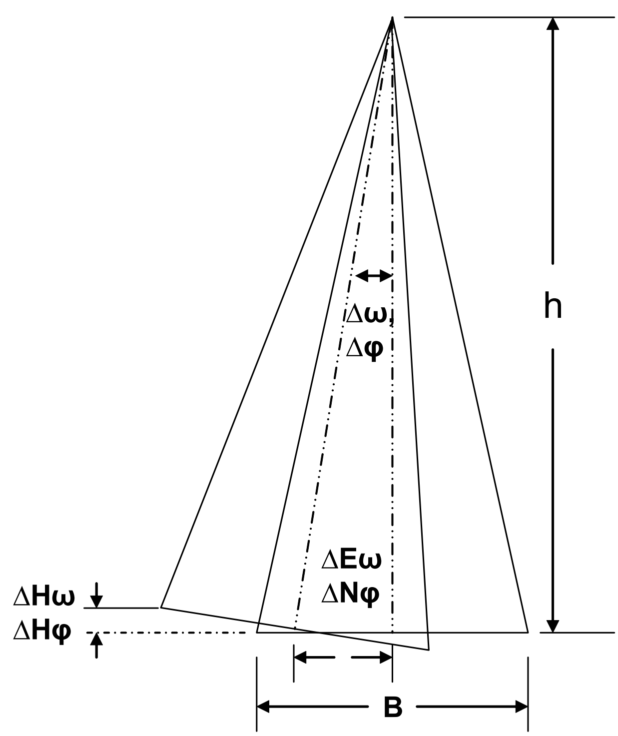

Figure 1. Effect of omega and phi on map positioning

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The symbols presented in Figure 1 are as follows:

h = Flying altitude

FOV = Lens field of view

B = camera ground coverage = **h . tan (FOV)**

$\Delta\omega$ = error in omega determination

$\Delta\varphi$ = error in phi determination

$\Delta\kappa$ = error in kappa determination

Δ$\mathbf{E}\omega$ = error in **E**asting coordinates caused by $\Delta\omega$ = **h . tan ($\Delta\omega$)**

Δ$\mathbf{N}\varphi$ = error in **N**orthing coordinates caused by $\Delta\omega$ = **h . tan ($\Delta\varphi$)**

Δ$\mathbf{H}\omega$ = error in **H**eight caused by $\Delta\omega$ = **½ h . tan (FOV)**

Δ$\mathbf{H}\varphi$ = error in Height caused by $\Delta\varphi$ = **½ h . tan (FOV)**

Similar derivation can be made for the effect of errors in kappa on the map's coordinates which results in the following error equation:

Δ$\mathbf{E}\kappa$ = error in **E**asting coordinates caused by $\Delta\kappa$ = **½ h . sin ($\Delta\kappa$)**

Δ$\mathbf{N}\kappa$ = error in **N**orthing coordinates caused by $\Delta\kappa$ = **½ h . sin ($\Delta\kappa$)**

where,

$\Delta\kappa$ = error in kappa determination

Based on the previous relations, one can stand on map errors caused by errors in sensor orientation alone, bearing in mind that other errors may exist throughout the mapping process. Table 3 provides high level, worst case scenario error modeling affecting the planimetric coordinates of the map due to 10 arcsec errors introduced into each of the sensor orientation angles ω, φ, and κ. It is obvious from Table 3 that these errors are directly proportional to the flying altitude.

2) **Degradation in Image Quality:** Over scanning may negatively affect the scanned image. For each film there is a threshold for fine scanning resolution beyond which signal-to-noise ratio during the scanning process may negatively affect the scanned image quality. Such noise may result either in bad image quality or perhaps the scanned details do not reflect the quality expected from the finer resolution as the original film does not have this level of details due to the coarse photography scale.

"it is only possible to stretch the flying altitude to a limit beyond which it becomes impossible to meet the accuracy for the intended map."

Table 3 may provide some explanation on how users were able to increase the flying altitude while still meeting the accuracy requirements of the map. Let us look into the map accuracy requirements for each of the flying altitudes given in Table 2 to figure out whether there is enough safety factor modeled in the required accuracy figures. Table 4 reflects the accuracy figures according to ASPRS class I standard for maps produced from film flown with each of the given flying altitudes.

Upon careful examination of Table 4, one appreciates the amount of error contributed by the camera orientation angles, which is considered the major error source in photogrammetric modeling. There is a factor of 2.9 between the allowed error, according to the ASPRS standard, and the maximum error introduced by the orientation angles. Additional error sources will be introduced to the final map accuracy figure. However, errors caused by erroneous camera orientation angles remain the largest contributor, as automation in the mapping process and the advanced softcopy technologies and modeling software employed in today's map making have reduced or eliminated many of the error sources that existed in the early days of the paper-based map making process. For this and other reasons, we are able today to produce maps with accuracy that greatly exceeds any requirements by any of the well known map standards.

Table 3. Errors estimation from different flying altitude.

h (ft)	ΔEĐ (ft)	ΔNĐ (ft)	ΔEĐ (ft)	ΔNĐ (ft)	ΔEĐ+ΔEĐ	ΔNĐ+ΔNĐ	Circular Error (ft)
1,800	0.087	0.087	0.087	0.087	0.175	0.175	0.247
3,600	0.175	0.175	0.175	0.175	0.349	0.349	0.494
7,200	0.349	0.349	0.349	0.349	0.698	0.698	0.987
14,400	0.698	0.698	0.698	0.698	1.396	1.396	1.975

Table 4. Maps error budget according to ASPRS standard.

h (ft)	ΔEĐ+ΔEĐ	ΔNĐ+ΔNĐ	Circular Error	ASPRS Class I Accuracy		
				Map Scale	RMSE in E or N (ft)	Circular RMSE (ft)
1,800	0.175	0.175	0.247	1"=50'	0.50	0.707
3,600	0.349	0.349	0.494	1"=100'	1.00	1.414
7,200	0.698	0.698	0.987	1"=200'	2.00	2.828
14,400	1.396	1.396	1.975	1"=400'	4.00	5.657

Table 5. Relationship between image GSD and mapping scale.

Image GSD (m)	Ortho GSD (m)	Supported Map Scale	Supported Contour Interval (m)
0.15	0.15	1:1,200	0.60
0.30	0.30	1:2,400	1.50
0.60	0.60	1:4,800	3.00

The same arguments apply to today's digital mapping sensors. However, it is not practical to use accuracy criteria that is mainly defined by flying altitude as is the case with film cameras, as manufacturers of digital sensors followed different design philosophies and produced digital sensors with different sensor (CCD array) size, Charge Coupled Device (CCD) size, and lenses focal lengths. This has also resulted in unusual image scales and enlargement ratios as compared to the familiar scale and enlargement ratio from film-based imagery, as you mentioned in your question. Map scale and enlargement ratio have no meaning in the digital world of mapping products. Most users, if not all, perform image analysis and measurements on screen by zooming 200% to 300%. Lacking mapping standards that define map accuracy in terms of GSD and not map scale, we adopted accuracy figures that we devised for scanned film used in a softcopy environment. Referencing accuracy in term of image acquisition GSD is probably the best strategy. Map providers should be responsible about choosing the sensor type and flying altitude as long as they provide the contracted GSD and accuracy requirements. In the past decade, we have employed accuracy figures required for products from aerial digital sensors using the associations and assumptions provided in Table 5. Therefore, the given figures can be used for products generated from the new digital sensors assuming that all final products will be produced with GSD equal to the native GSD of the raw imagery.

"Map scale and enlargement ratio have no meaning in the digital world of mapping products."

Finally, we are finding out that due to a combination of improved mapping practices, the superb quality of digital aerial sensors, and processing algorithms and software, users are capable of producing mapping products that far exceed the geometrical and radiometric quality of the film cameras. This improved quality offered flexibility in designing digital sensors and provides users with the freedom to fly projects from higher altitudes in order to reduce acquisition costs. Some of the modern digital sensors are manufactured with lenses that have a longer focal length and smaller (CCD) size that allows users to fly higher while maintaining high image resolution of the ground, similar to the concept of scanning film with higher scanning resolution, as discussed above. The new digital sensors also allow us to define new accuracy figures that are stricter than the figures assumed for the scales given in Table 5. More on this subject can be found in previous "Mapping Matters" columns, especially in PE&RS issues May 2009, July 2007, June 2008, May 2009, March 2010, August 2010, September 2010, and October 2010.

Please send your question to Mapping_Matters@asprs.org and indicate whether you want your name to be blocked from publishing.

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