Higher Camera Resolution - When it Helps and When it Hurts

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This whitepaper discusses the trade-off between camera resolution and image smear in small UAV and multi-rotor Precision Agriculture applications. Image quality, measured in terms of image smear in pixels, is one important factor which enters into a system integrators choice of camera resolution. This analysis should enable systems integrators to make more informed decisions when selecting the camera resolution that is appropriate for their applications....

1 Introduction

The precision agriculture market is very dynamic. The systems integrator must quickly identify and integrate leading-edge technology into their products to remain competitive. In the commercial small UAV and multi-rotor markets which serve Precision Agriculture, one important system tradeoff that must be made is the choice of camera resolution. There appears to be a misconception in the industry that higher megapixel cameras always produce better quality imagery. In reality, higher megapixel cameras can provide worse, the same, or better quality imagery depending upon how they are used and the conditions under which they are used. The purpose of this white paper is to clarify the conditions under which higher resolution is beneficial or detrimental. The ultimate test between cameras with different resolutions is a comparison between the images that are produced under the same set of conditions. It is well known in photography that an average quality camera in the hands of an expert photographer can produce excellent quality images, whereas an outstanding quality camera in the hands of a poor photographer will usually produce poor quality images. Image quality is critically dependent on how a camera is used and on the conditions under which it is used. Sentek has performed multiple system level design trades-offs to identify and optimize a Multi-spectral camera payload for use in Precision Agriculture.

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N_x (Pixels)	N_y (Pixels)	N_xN_y
$1,280$	$1,024$	1.3 MP
$2,048$	$1,536$	3.1 MP
$4,000$	$3,000$	12 MP
$6,048$	$4,032$	24.4 MP

Table 1: Selected camera focal plane array pixel densities. MP denotes "Megapixels".

2 Camera Resolution

The choice of camera resolution is dependent on the intended application. In certain applications it is possible to take full advantage of higher resolution cameras, while in other applications higher resolution cameras may offer no advantage. As a basis of comparison, in this paper we will use a collection of 4 sensor resolutions that are currently being used in Precision Agriculture applications (see Table 1). In applications where the camera is stationary or moving and rotating slowly, higher resolution cameras can produce higher quality images than lower resolution cameras. However, as the translational speed of the camera increases we must consider the distance the camera moves during the image exposure time, E. For example, consider Table 2, where V is the camera translational speed in knots (i.e. nautical miles per hour) and $V * E$ is the distance the camera moves during a typical camera exposure time of one millisecond ($E = 1 * 10^{-3}$ seconds).

V (knots)	$V * E$ (cm)
30	1.5
60	3.1
90	4.6
120	6.2

Table 2: Distance traveled during 1 ms camera exposure time

Hence, if the camera is translating at a speed of 30 knots it will move 1.5 centimeters during a camera image exposure time of 1 ms.

At a given instant in time, a single pixel in a cameras focal plane array sees a patch of ground of a certain size. The length of one of the edges of this patch is called the *Ground Sampling Distance*, or GSD. Let f denote the focal length of our lens, and let H denote the distance between the camera and the ground (platform height). Also, let P_x and P_y denote the length and width of a single pixel element in the focal plane array (i.e. the dimensions of a single photoreceptor). This is sometimes called the pixel pitch. Then, the size of the patch that a pixel sees is approximately[2] given by (see [1] or [2, p. 50]):

$$\text{GSD}_x = \left(\frac{HP_x}{f}\right), \quad \text{GSD}_y = \left(\frac{HP_y}{f}\right) \tag{1}$$

The units used for pixel pitch must match those used for H and f. GSD will then be in the same units. Frequently, imaging sensors use square pixel elements, meaning that $P_x = P_y$ (while not all sensors have square pixels, it is very common). Thus, it is often the case that $\text{GSD}_x = \text{GSD}_y$. For simplicity, we will make this square pixel assumption and drop the subscript x or y on GSD.

In practice, the optics for a camera will be selected to achieve a specific field of view (FOV). Thus, it can be helpful to use the following equation to estimate GSD based on sensor resolution and field of view. In this equation, FOV should be set to the horizontal field of view for the camera and N should be the number of pixels in one row of the focal plane array (one can alternatively use vertical field of view and the number of pixels in a single column).

$$\text{GSD} = \frac{2H\tan(\text{FOV}/2)}{N} \tag{2}$$

During the camera exposure time the patch of ground that is seen by an individual pixel changes due to camera motion. This causes the image to smear (sometimes called motion blur). To reduce image smear we would like for the distance that the camera moves during the image exposure time (i.e. $V * E$ in Table 2) to be small relative to the GSD.

We can use use Equation 2 for a given field of view (we use 30 degrees) to estimate the GSD for various sensor resolutions and platform altitudes. Note that currently the maximum altitude that small unmanned air systems (SUASs) are legally allowed to fly in the United States is 400 ft $= 121.92$ m $= 12,192$ cm:

N_x	GSD at 100 ft	GSD at 400 ft
1,280	1.3 cm	5.1 cm
2,048	0.8 cm	3.2 cm
4,000	0.4 cm	1.6 cm
6,048	0.3 cm	1.1 cm

Table 3: Ground sampling distances for a UAV flying at 100 ft and 400 ft with a 30 degree horizontal field of view for cameras with pixel densities given in Table 1. N_x is the number of pixels in a single row of the imaging sensor.

The ratio of the distance traveled by the camera during the image exposure time ($V * E$ in Table 2) to the ground sampling distance (GSD) is a measure of the image smear.

$$\text{Smear} = \left(\frac{VE}{\text{GSD}}\right) \tag{3}$$

[2] This approximation is valid when the distance from the lens to the scene is much larger than the lens focal length.

If this ratio is larger than 1 then the image seen by an individual pixel at the beginning of the exposure time is completely different than the image seen at the end of the exposure time. Images can still have acceptable quality with this level of smear, but the "effective resolution" of the imagery is lower than the physical sensor resolution. In other words, the advantage of the higher sensor resolution has been lost. Table 4 summarizes the image smear for the scenarios in Table 3. It is also important to note that these computations only take into account the smear due to translational motion of the camera. The camera is also rotating due to the constant pitching and rolling of the air vehicle. Depending on the stability of the platform and how the cameras are mounted and stabilized, the smear due to vehicle rotation can exceed the smear due to translational motion. Thus, these calculations are rather optimistic and real-world smear may be considerably higher for some systems.

N_x	Smear at 100 ft	Smear at 400 ft
1,280	1.15	0.29
2,048	1.88	0.47
4,000	3.75	0.94
6,048	5.00	1.36

Table 4: Camera smear in pixels for a 30 knot UAV for the GSDs depicted in Table 3.

From these tables, it is clear that for SUAS speeds of 30 knots or higher, and for common flight altitudes (ground-level up to 400 ft), the image smear incurred by the higher resolution imagers counterbalances the advantage of higher sensor resolution.

There are three ways to try to take advantage of higher camera resolutions: widen the field of view, fly higher, or fly slower. The first two strategies achieve a reduction in smear by increasing the GSD. Thus, imagery collected in this way is not any sharper than the smeared imagery (it is like zooming out until the smearing is not noticeable). However, by increasing the GSD, there is an advantage in the form of improved coverage rate. It should be noted that both of these strategies can be problematic. First, flying higher may not be allowed by local laws and regulations. Second, increasing the field of view can result in greater crop shadowing (depending on crop height). This can cause apparitions in computed vegetative indices and it can reduce the robustness and visual quality of photo-mosaics. The 30 degree FOV used above was set based on crop shadowing for corn late in the growing season. It is computed (in radians) based on crop height and crop spacing using equation 4:

$$FOV = 2\left[\frac{\pi}{2} - tan^{-1}\left(\frac{\text{crop height}}{\text{row spacing}}\right)\right] \quad (4)$$

Earlier in the growing season, when the crop height is lower, wider fields of view can be used without these adverse effects, but users and integrators should be aware that those fields of view are not appropriate for all situations and the optics may need to be changed or reconfigured for other situations.

The third strategy of flying slower reduces smear without sacrificing GSD. This is an option for multirotor vehicles. However, fixed-wing vehicles have a minimum speed that they must maintain to avoid stalling. Even if it is possible to fly slower, this comes at the expense of coverage rate; this must be taken into account when considering this option.

There would seem to be a fourth strategy to reducing smear, which would be to simply shorten camera exposure time, E. This decreases the distance that the camera moves during image exposure, $V * E$, which in turn decreases smear. Unfortunately, ultrashort exposure times frequently bring with them a whole new set of problems. The nature of these problems varies depending on sensor technology and shutter type, but may include higher noise, linear distortion, or streak-like artifacts due to lower shutter efficiency. A thorough treatment of these effects is beyond the scope of this document, but a discussion can be found in the Sentek Technical Report "Selecting Camera System Parameters To Achieve Mis-

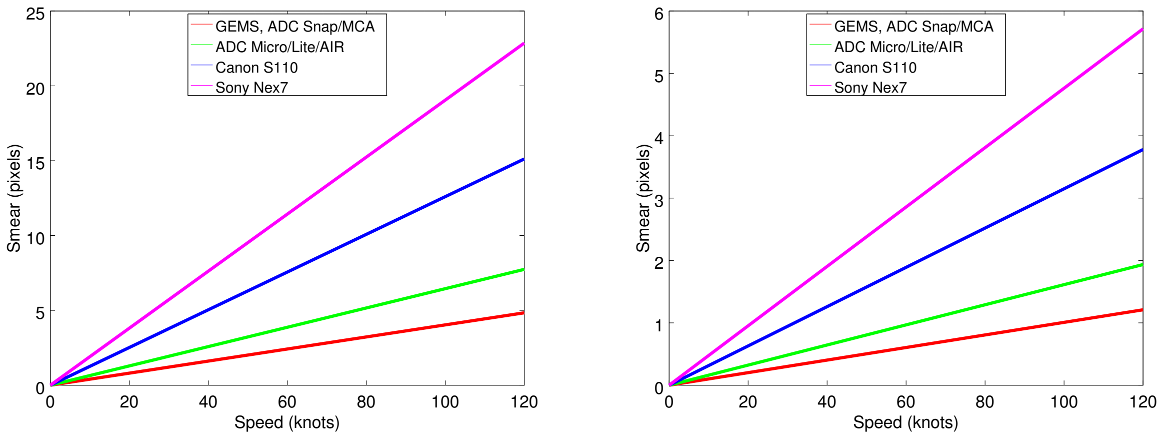

Figure 1: Image smear due to translational motion for cameras in Table 5, assuming a 30 degree FOV and flying at an altitude of 100 ft (left graph) or 400 ft (right graph).

sion Objectives". Different cameras will have different lower bounds on exposure time (where image quality is still acceptable), but few commercially available cameras can go well below 1 ms without compromising image quality in some way. It should be noted that some higher-resolution imagers on the market shrink pixel pitch (P_x and P_y) to squeeze the larger number of pixels into a small, standard package size (this is not the case with "full-frame" DSLR cameras, but it is often the case with smaller form-factor, high-resolution sensors). This tends to result in lower light sensitivity since the individual pixel elements are collecting photons over a smaller area. This can make it much more difficult to achieve acceptable image quality at lower exposure times (this is the reason that imagery collected with some ultra-high resolution cameras can actually be worse than imagery taken with lower-resolution sensors). For the purpose of the present analysis we fix the exposure time parameter across cameras.

Figure 1 depicts image smear as a function of speed over the ground for several cameras commonly used in the precision agriculture market (see Table 5). This assumes that optics have been configured for a 30 degree field of view (FOV). Results are presented for flight altitudes of 100 ft and 400 ft.

Camera Name	N_x (Pixels)
GEMS	$1,280$
ADC Snap	$1,280$
ADC MCA	$1,280$
ADC Micro	$2,048$
ADC Lite	$2,048$
ADC AIR	$2,048$
Canon S110	$4,000$
Sony Nex 7	$6,048$

Table 5: Pixel densities for the cameras depicted in Figure 1

In Sentek's experience, cameras obtain excellent image quality when the image smear (Equation 3) is less than or equal to .3 pixels, very good image quality when the image smear is between .3 and .6 pixels, and acceptable image quality for an image smear of 1 pixel.

In practice, the image quality degrades gradually as the image smear increases, and images with a few pixels of image smear may still look quite good even though the images are effectively no longer achieving the stated resolution.

2.1 When Can We take Advantage of Higher Resolution Cameras?

High resolution cameras are well suited for applications where there is little or no motion during the camera exposure time (i.e. $V * E$ is zero or very small). For example a camera mounted on a stable, hovering or slowly moving multi-rotor platform or on a stationary vehicle.

High resolution cameras are also well suited for manned aircraft that are legally allowed to fly at altitudes higher than 400 ft since by flying higher you can increase the GSD, thereby decreasing image smear (i.e. for a fixed $V * E$). Flying higher and increasing the ground sampling distances also enables the platform to fly at faster speeds typical of manned aircraft. This in turn increases the coverage rate.

3 Summary

We have considered some of the factors that impact image quality and quantified their impact in the form of image smear (Equation 3). While there certainly are situations where ultra-high resolution cameras can provide additional benefit, the GEM system's cameras and optics provide a FOV and GSD that are highly appropriate for small multi-rotor and small fixed wing UAVs flying at or under 400 ft at speeds up to approximately 30 knots (or faster when flying at the upper end of that altitude range: see Figure 1). There are additional factors that impact image quality, image mosaicing, registration accuracy, and coverage rate. For a discussion of these other important parameters, the reader is directed to the Sentek Technical Report "Selecting Camera System Parameters To Achieve Mission Objectives".

References

[1] R. I. Hartley and A. Zisserman. *Multiple View Geometry in Computer Vision*. Cambridge University Press, ISBN: 0521623049, 2000. 2

[2] Y. Ma. *An invitation to 3-D vision: from images to geometric models*. Interdisciplinary applied mathematics: Imaging, vision, and graphics. Springer, 2004. 2

