Guide to Spatial Imagery Digital Imagery Spatial Resolution

This guideline discusses commonly used spatial resolution metrics illustrated with image simulations. The purpose is to assist the remote sensing community – image users and buyers, as well as image providers and even sensor designers – by visually demonstrating how certain image specification parameters affect spatial resolution. Several examples of imagery show first-hand how these parameters influence image quality.

The guideline provides a high-level tutorial describing how spatial resolution is specified, as well as a catalog of images so the user can relate these specifications to image products. The general user should be able to easily cover the material included in the main text. Sidebars provide greater detail to the interested reader, and references and hyperlinks to comprehensive explanations and discussions provide more details for those desiring an in-depth understanding. The main text discussion is followed by a set of simulated image chips, which are available for download so that the user may adjust their display (zoom/stretch).

This guideline is applicable to imagery that is:

- Acquired with passive electro-optical (EO) imagers operating in the visible spectral region
- Both color and monochrome (panchromatic)
- Nadir or down looking
- Native and not sharpened
- High or moderate resolution (between 5 cm and 10 m GSD)
- Acquired with imagers that have well behaved system-level symmetrical or Gaussian-like shaped Point Spread Functions (PSFs)-discussed later.
- High Signal-to-Noise

Why Use Simulated Imagery?

Final image product resolution depends not only on a camera’s properties, but also on how an image is acquired and what image processing algorithms are applied. Different platforms – aircraft, satellite, small Unmanned Aerial Vehicles (UAVs) etc. -- and different installations affect imagery differently. Flight conditions such as sun angle, haze, and height above target area etc. also affect image quality. Comparing imagery acquired and processed under one set of conditions with imagery acquired and processed
under a different set of conditions makes it difficult or even impossible to separate camera specification effects from image processing and image acquisition effects. By simulating imagery, we remove image acquisition and processing variability from this discussion. While the imagery shown is for a specific set of conditions, the simulations only vary spatial resolution parameters for that set of conditions.

What is Spatial Resolution?

Spatial resolution determines the smallest discernable feature within an image (Holst, 2006). Often, the spatial resolution of remotely sensed imagery is described only in terms of pixel spacing, or **Ground Sample Distance (GSD)**.

![Example imagery with a 15 cm GSD](image1.jpg) ![Same image area at 1 m GSD](image2.jpg)

While significant, GSD is only one aspect of spatial resolution. Two other important features that affect image quality and interpretability are **image sharpness**, or blur, and image noise, often referred to as **Signal-to-Noise Ratio (SNR)**. Here we will highlight the effect of image sharpness and GSD on image quality. SNR effects will be discussed on a separate page. Within this guideline, all simulated imagery has a high SNR that exceeds 100 throughout most of the scene (except for shadows).
Two images can have the same GSD but different levels of image sharpness and look very different.

Imagery at 15 cm GSD; Image is in focus. Image Sharpness “Good”.

Imagery at 15 cm GSD; Image is blurry. Image Sharpness “Poor”.

Why is Spatial Resolution Important?

Spatial resolution can impact the usefulness of a data set for different applications. Some applications may involve identification of small objects such as man-hole covers, letters on a roadway, or roof damage after a storm, while others may focus on large features like agricultural fields that cover a large area.

An understanding of the effects of GSD and image sharpness can guide data acquisition parameters, such as acquisition height or image stabilization requirements. Spatial resolution can affect a person’s ability to extract useful information from imagery. Understanding spatial resolution can help optimize the amount of data needed, aid image quality assurance, and even drive camera design.
Sensors are being developed with improved optics (detector limited sensors). Image sharpening algorithms that improve image quality also exist. Sharper images, however, are not always better images. Data sets that are detector limited can be over-sharpened and will appear pixelated, or **aliased**. Aliasing causes fringing patterns, such as Moiré patterns, that are not physically present in a scene to appear in an image.
Remote sensing image end users or data providers may opt to trade GSD for image sharpness when acquiring data sets. A blurrier data set that has a smaller GSD could provide the same level of detail as a sharpened, slightly aliased data set with a larger GSD, but the latter may be preferred because it may cover a larger area of interest. The following table summarizes some of the image acquisition aspects that are affected by image sharpness.

<table>
<thead>
<tr>
<th>Image Acquisition/ Sensor Parameters</th>
<th>Lower Image Sharpness</th>
<th>Higher Image Sharpness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scene Size</strong></td>
<td>GSD must be smaller, so more pixels needed to cover same area (More data storage required)</td>
<td>GSD can be larger so less pixels needed to cover same area (Less data storage required)</td>
</tr>
<tr>
<td><strong>Scene Brightness (Light Level)</strong></td>
<td>Bright Scenes / Panchromatic (Lower SNR)</td>
<td>Dark Scenes / Color (Higher SNR)</td>
</tr>
<tr>
<td><strong>Image Motion</strong></td>
<td>More susceptible</td>
<td>Less susceptible</td>
</tr>
<tr>
<td><strong>Optics Size</strong></td>
<td>Smaller</td>
<td>Larger</td>
</tr>
</tbody>
</table>


Additionally, spatial resolution is a component of the National Imagery Interpretability Rating Scale (NIIRS) used by the National Geospatial-Intelligence Agency to assess image utility.

**How is Image Sharpness Defined?**

Image sharpness can be defined in several different ways. But before these can be described, first we need to understand what happens when a remote sensing imager acquires an image.
Image Sampling

In remote sensing, image sampling refers to converting an observed continuous spatial signal into a discrete, digitized image. The size of the sensor’s detectors and optics control the sampling rate. Combined with the sensor focal length and distance between the sensor and the object being imaged, the sampling defines the ground sample distance.

$GSD \approx \frac{d}{f \cdot z}$
When an electro-optical imaging system measures light from a single point, or point source, the light is not acquired by a single detector. Rather the light is spread over and measured by several detectors. This point source system response is a result of a measurement system’s detectors and optics and is called the system **Point Spread Function (PSF)**. PSF therefore is a measure of how sharp an imaging system can acquire imagery. In practice, however, a measurement system’s PSF is very difficult to directly measure due to SNR and sampling considerations.
When an electro-optical system images a feature such as an edge formed by adjacent dark and bright areas, the PSF blurs the edge contrast in the resulting image. This process is mathematically equivalent to **convolving** the PSF with the edge. (Boreman 2011, Gaskill 1978, Goodman 2008).

**Targets**
Specially engineered resolution targets, such as edges or tribars are often used to quantify image sharpness. Edges are particularly useful since all the appropriate information can be derived from a high quality (high SNR) edge response without incurring sampling issues. Edges are also good because they occur naturally throughout many urban and agricultural scenes and, properly screened, can be used to evaluate spatial resolution. Tribars are good for quick visual checks of the minimum resolvable target size.
Measures of Image Sharpness

Image sharpness can be defined using either spatial data (measured as a function of X and Y) using physical features or spatial frequency data (measured as a function of \( u \) and \( v \)) using Fourier analysis. When spatial data is used, the assessment is said to be in the **Spatial Domain**. When spatial frequency data is used, the assessment is said to be in the **Frequency Domain**. We describe both types of measures below. The following figure introduces several terms from both perspectives - spatial and frequency - and generally outlines how they relate to each other mathematically.

<table>
<thead>
<tr>
<th>Spatial Domain Measures</th>
<th>Frequency Domain Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Relative Edge Response</td>
<td>• Modulation Transfer Function (MTF) at Nyquist</td>
</tr>
<tr>
<td>• Full Width Half Maximum (FWHM) of the Line Spread Function (LSF)</td>
<td>• MTF at half Nyquist</td>
</tr>
<tr>
<td></td>
<td>• MTF50</td>
</tr>
</tbody>
</table>
Adapted from Schowengerdt, Robert A., Remote sensing models and methods for image processing, Elsevier 2007.

Image sharpness measure relationships
Image sharpness can be found using an imaged edge by measuring how quickly the image transitions from dark to bright. This can be achieved through Edge Sampling, an important aspect of producing an accurate edge response from an imaged edge. A single transect across the edge, or multiple transects across an edge that is perpendicular to the image area, will produce a sparse set of points that will not accurately represent the edge.

Edge sampling is used to improve edge sampling (ISO 12233: 2000). Multiple transects across a tilted edge ensure proper sampling across the entire edge to avoid aliasing, which produces a more accurate edge response.
accomplished by looking at the **Edge Spread Function** or normalized **Edge Response**. To produce an Edge Response, transects across an edge are aligned and centered, and the values are normalized to one.

![Edge Response (ER) curve generation](image)

In practice an edge response curve may contain many features including ripple, and overshots and undershoots. These can be caused by the non-ideal physical condition of an edge target or by edge sharpening or other image processing algorithms used by sensor manufacturers and image providers.
In the Landsat community, **Edge Response Slope** is an additional edge response-based measure of spatial performance.

The Edge Response Slope is defined as the slope between the 40% and 60% edge response points defined using distance (meters or feet), rather than pixels. The Edge Response Slope represents the distance required for a system to achieve a 20% change in contrast around the edge center.
**Note:** To best understand an imaging system’s performance, measurements should be made using raw, radiometrically corrected data. Otherwise, if measurements are made using resampled, geometrically-corrected or terrain-corrected data, the spatial performance measures will also include processing effects introduced by the entire image processing chain.
Landsat Spatial Resolution: Half Edge Extent

In the Landsat community, **Half Edge Extent** is an additional edge response-based measure of spatial performance.

The Half Edge Extent is defined as either the horizontal distance (meters or feet) between the 5% and 50% edge response points (lower), or the 50% and 95% edge response points (upper). **The Half Edge Extent measures the contrast transition distance on either side of an edge.** An asymmetry in the system PSF could result in differences between the upper and lower Half Edge Extent values.
Several measures of image sharpness, or spatial performance, can be directly found from the normalized Edge Response. A common spatial performance metric is the **Relative Edge Response (RER)**. The RER is defined as the slope (steepness) of the Edge Response within ±0.5 pixel of the center of the edge. *The RER represents how an imaging system responds to a change in contrast over one pixel.* Higher RER values resulting from steeper edges indicate a sharper image. Lower RER values indicate a blurrier image.

**Relative Edge Response (RER) calculation**
Alternate Spatial Domain Measures

**Landsat Spatial Resolution: Aliasing**

The Landsat community introduced an aliasing specification that requires:

\[ \text{Edge Slope} \times \text{GSD} < 1.0 \]

This restriction attempts to guarantee there is some overlap between the system level PSFs when sampled at the instrument GSD to prevent aliasing. The system GSD can be less than the product GSD.
Additional spatial measures of image sharpness can be determined from an imaged edge. Taking the derivative of normalized Edge Response produces the **Line Spread Function (LSF)** (Gaskill, 1978; Boreman, 2001). The LSF is a 1-D representation of the system PSF. The width of the LSF at half the height (the 50% point) is called the **full-width at half maximum (FWHM)**. *The FWHM of the LSF represents the width of the integral of the system PSF in one direction.*

![Line Spread Function (LSF)](image)

**Note:** Because a system PSF is not necessarily symmetrical, edges in multiple directions should be assessed.
Frequency Domain Measures

Image sharpness can also be quantified in the frequency domain. The Fourier Transform of the LSF produces the Modulation Transfer Function (MTF) (Gaskill, 1978; Boreman, 2001; Goodman, 2008; Holst, 2006). The MTF measures the change in contrast, or modulation, of an optical system’s response at each spatial frequency.

To better understand spatial frequency, consider the following: Let’s suppose there is a target within the field of view of an imaging system that alternates in brightness just as a sine wave would. The target’s brightness cycles up and down with distance just as a sound wave, measured in Hz, cycles up and down with time.

Higher spatial frequencies to the right correspond to fine image detail, while lower spatial frequencies to the left correspond to less detail. In practice, the point at which the target could no longer be resolved would determine the spatial resolution.

NOTE: Spatial frequency targets like the one shown would be too large to maintain for large-GSD sensors (satellites). However, for small-GSD sensors, such as those flown on UAVs, they may become more practical.
MTF is determined across all spatial frequencies, but can be evaluated at a single spatial frequency, such as the Nyquist frequency. Nyquist frequency is defined to be 0.5 cycles per pixel and is the highest spatial frequency that can be imaged without causing aliasing. In an example at the Nyquist frequency, the target input signal and imaging sensor output response may look like the following. Dividing the output response by the input signal gives the value of the MTF at that particular spatial frequency.

The value of the MTF at the Nyquist frequency is a common measure of image sharpness. The value of the MTF at Nyquist provides a measure of resolvable contrast at the highest ‘alias-free’ spatial frequency. A sample MTF curve with Nyquist highlighted is shown below.
Images with higher MTF at Nyquist values will be sharper but may have aliasing, while images with lower MTF at Nyquist values will be blurred. Typical MTF at Nyquist values for imaging sensors range from 0.1 to 0.4.

Additional frequency domain measures of image sharpness are the **MTF at Half Nyquist** and the **MTF50** value. MTF50 is the frequency corresponding to the 50% point of the normalized MTF curve. While used less frequently, both of these measures provide additional information about the imaging system’s spatial performance. Due to optical effects such as obscuration, which affect mid-range spatial frequencies, acquired images can have MTF curves with the same MTF at Nyquist but very different shapes, resulting in differences in image quality. *The MTF at Half Nyquist and the MTF50 value provide insight into the shape of the MTF curve*, giving additional knowledge of image sharpness and spatial performance.
MTF curve showing MTF measured at several different frequencies
Additional target frequencies alongside an imaging sensor’s output response.
## Summary of Spatial Resolution Metrics

<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter</th>
<th>Description/Benefits</th>
<th>Shortcomings</th>
<th>Calculation/Measurements</th>
</tr>
</thead>
</table>
| Spatial | GSD or Ground Pixel Size | • Sampling distance (center-to-center distance between pixels)  
• Most common metric, most representative when imaging is detector limited (detectors larger than PSF)  
• Simple to measure or calculate | Does not account for blur associated with optics, motion and processing | Distance between two points on the ground divided by the number of pixels between points  
Common units: [meters or pixels] |
| Spatial Frequency | Nyquist Frequency | • The minimum sampling rate without aliasing (frequency sampling limit)  
• Used in MTF@Nyquist and MTF@1/2 Nyquist | Does not account for blur associated with optics, motion and processing | 1/(2*GSD) or 1/(2*pixels)  
Common units: [cycles/meter or cycles/pixel] |
<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter</th>
<th>Description/Benefit</th>
<th>Shortcomings</th>
<th>Calculation/Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td><strong>FWHM of the Line Spread Function (LSF)</strong></td>
<td>• Measure of sharpness</td>
<td>Only one measure</td>
<td>Derived from a line source or derivative of edge response Common units: [meters or pixels]</td>
</tr>
<tr>
<td></td>
<td><strong>LSF Extent</strong></td>
<td>• Defines an effective extent</td>
<td>Secondary measure; requires other metrics</td>
<td>Defined at some threshold, e.g. 5% Common units: [meters or pixels]</td>
</tr>
<tr>
<td></td>
<td><strong>Relative Edge Response (RER)</strong></td>
<td>• Contrast change over one pixel on a normalized edge response</td>
<td>Only one measure typically at mid frequency range</td>
<td>Derived from edge response ER(+0.5) – ER(-0.5) Common units: [dimensionless]</td>
</tr>
<tr>
<td></td>
<td><strong>Edge Extent</strong></td>
<td>• Defines distance required for contrast change in center of edge response</td>
<td></td>
<td>Defined at some threshold i.e. 5% and 95% Common units: [meters or pixels]</td>
</tr>
<tr>
<td>Spatial Frequency</td>
<td><strong>MTF50</strong></td>
<td>• Half-width half maximum spatial frequency of the MTF</td>
<td>Only one measure at the mid frequency range. Does not describe the MTF at other spatial frequencies</td>
<td>Spatial frequency at 50% MTF value Common units: [cycles/meter or cycles/pixel]</td>
</tr>
<tr>
<td></td>
<td><strong>MTF@Nyquist</strong></td>
<td>• MTF value at Nyquist Frequency</td>
<td>Only one parameter. Does not describe the MTF at midrange and lower spatial frequencies</td>
<td>MTF value at Nyquist freq. Common units: [dimensionless]</td>
</tr>
<tr>
<td></td>
<td><strong>MTF@1/2 Nyquist</strong></td>
<td>• Value of the MTF at half the Nyquist frequency</td>
<td>Only one measure at the mid frequency range. Does not describe the MTF at other spatial frequencies</td>
<td>MTF value at ½ Nyquist freq. Common units: [dimensionless]</td>
</tr>
</tbody>
</table>
Q-effective and a Way to Classify Imagery

One way to look at spatial resolution is to compare the FWHM of the LSF to the GSD of the imaging system. Relating the system PSF to GSD can define blur, but because the LSF is a measure more routinely used and easier to determine, we use it here rather than the system PSF. Let’s define a parameter called Q-effective such that:

\[
Q_{\text{effective}} = \frac{\text{FWHM of the LSF}}{\text{GSD}}
\]

If the FWHM is approximately equal to the GSD, the imaging system is slightly aliased. If Q-effective is greater than 1, the FWHM of the LSF is larger than the GSD and therefore the imagery appears blurry. On the other hand, if Q-effective is less than 1, the FWHM of the LSF is smaller than the GSD and the imagery appears aliased. Typical imaging sensors operate with Q-effective between 1 and 1.5 (balanced).

The effect of varying Q-effective values on a point source signal is shown below. When Q-effective is greater than 1, the signal from the point source is blurred over a large area. When Q-effective equals 1, the blur is reduced. When Q-effective is less than 1, the majority of the signal stays within the same pixel.

Detector/Blur Balancing

The size of the system PSF compared to the size of the detectors will affect the output image sharpness. If the PSF is much larger than the detectors, the system is said to be Optics Limited, and the output images will be blurry. If the PSF is smaller than the detectors, the system is Detector Limited, and the image will be aliased. When the width of the PSF is the same size as 2*detector (Nyquist Sampling), the resulting image will be neither too blurry or aliased. Balanced detection balances image sharpness against aliasing.
Q and Q-effective

Q is a parameter that relates an imaging sensor’s diffraction limited optical PSF width to its sampling distance (Fiete 2010). Since many optical systems are not diffraction limited, defining a parameter that makes use of diffraction limited PSF widths may not representative.

Alternatively, one can define Q-effective which includes all of the effects (detector, optics, motion, electronics, etc.) that contribute to the PSF. Since the LSF is a measure more routinely used and easier to determine, we replace the PSF with the LSF and define Q-effective as:

\[ Q_{\text{effective}} = \frac{\text{FWHM of the LSF}}{\text{GSD}} \]

Q-effective > 1 (Blurry)  Q-effective = 1 (Aliased)  Q-effective < 1 (Very Aliased)
Point Spread Functions (top row) for different Q-effective values, applied to the input point source produces the output signals with different amounts of blur (bottom row)

To further illustrate this parameter let’s look at several spatial resolution parameters associated with an image of an edge.
Measured Performance
Simulated Image
Q-Effective = 2 “Blurry”

Edge Spread Function

Normalized Edge Response
RER = 0.45

Line Spread Function
FWHM = 2

MTF
- MTF@Nyquist = 0.03
- MTF@HalfNyquist = 0.42
- MTF50 = 0.22
Measured Performance
Simulated Image
Q-Effective = 1.5 “Balanced”
Measured Performance
Simulated Image
Q-Effective = 1 “Aliased”
Measured Performance
Simulated Image
Q-Effective = 0.5 “Very Aliased”

- **Edge Spread Function**
- **Line Spread Function**
- **Normalized Edge Response**
- **MTF**

- FWHM = 0.5
- RER = 0.97
- MTF@Nyquist = 0.8
- MTF@HalfNyquist = 0.95
- MTF50 = NaN
The following table summarizes the spatial resolution parameter values discussed above.

<table>
<thead>
<tr>
<th>Simulated Image Parameters (all GSD's)</th>
<th>Relative Edge Response (RER)</th>
<th>Full Width Half Maximum of Line Spread Function (FWHM)</th>
<th>Modulation Transfer Function @ Nyquist Frequency (MTF @ Nyquist)</th>
<th>Modulation Transfer Function @ Half Nyquist Frequency (MTF @ ½ Nyquist)</th>
<th>Frequency at 50% Modulation Transfer Function Value (MTF50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blurry Q-effective = 2.0</td>
<td>0.45</td>
<td>2.0</td>
<td>0.03</td>
<td>0.42</td>
<td>0.22</td>
</tr>
<tr>
<td>Balanced Q-effective = 1.5</td>
<td>0.58</td>
<td>1.5</td>
<td>0.15</td>
<td>0.62</td>
<td>0.30</td>
</tr>
<tr>
<td>Aliased Q-effective = 1.0</td>
<td>0.75</td>
<td>1.0</td>
<td>0.40</td>
<td>0.80</td>
<td>0.44</td>
</tr>
<tr>
<td>Very Aliased Q-effective = 0.5</td>
<td>0.97</td>
<td>0.5</td>
<td>0.8</td>
<td>0.95</td>
<td>0.88 (exceeds Nyquist)</td>
</tr>
</tbody>
</table>
Image Simulations

Simulations were performed to illustrate the effect of varying spatial resolution on different features. In all cases, a data set with a smaller GSD (higher resolution) was used as input to generate larger GSD (lower resolution) image products. The coarser GSD values are sufficiently large so the finite resolution of the input image has little to no effect on the output image. Different amounts of blur were added to simulate imagery with different Q-effective values. The blurred image was then resampled to produce imagery with varying GSD’s.

Image Simulation

Several “classes” of data, defined by their GSD, were simulated to cover the range of data types a remote sensing consumer might encounter. The data classes simulated were: Moderate Resolution Satellite, High Resolution Satellite and High Resolution Aerial. For each class of data simulated, 4 types of spatial performance, ranging from blurry through balanced to aliased, were produced. This table outlines the data simulations performed and provides information about the input data sources.
### Simulation Output Sensor Class

<table>
<thead>
<tr>
<th>Moderate Resolution Satellite</th>
<th>10 m</th>
<th>Worldview-3(^1)</th>
<th>1.33 m Multispectral 0.33 m Panchromatic</th>
<th>February 27, 2018 Washington DC</th>
<th>1) Airport 2) Road Interchange 3) Dense Urban Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GeoEye-1(^1)</td>
<td>1.90 m Multispectral 0.49 m Panchromatic</td>
<td>October 22, 2017 Sioux Falls, SD</td>
<td>1) Agricultural Fields 2) Road</td>
</tr>
</tbody>
</table>

| High Resolution Satellite | 1 m | Leica DMCIII Aerial\(^2\) | 0.1 m Multispectral 0.1 m Panchromatic | August 15, 2017 Heilbronn, Germany | 1) Urban Center 2) Road Intersection 3) Parking Lot 4) Agricultural Fields |

| High Resolution Aerial | 0.15 m 0.30 m 0.50 m 0.75 m 1.00 m | Leica DMCIII Aerial\(^2\) | 0.03 m Multispectral 0.03 m Panchromatic | May, 2018 Heilbronn, Germany | 1) Road Intersection 2) Homes 3) Agricultural Fields |

| | 0.15 m | UAV-Based Sony Nex-5T\(^3\) | 0.005 m Multispectral 0.005 m Panchromatic | June 22, 2018 Long Beach, MS | 1) Tennis Court 2) Parking Lot 3) Building |

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1. *Worldview-3* and *GeoEye-1* imagery were acquired by *DigitalGlobe, Inc* and provided to the USGS through the NextView Contract
2. *DMCIII Aerial* imagery provided by *Leica Geosystems*
3. *UAV-based Sony Nex-5T* imagery acquired by *Innovative Imaging and Research*.

Multispectral image simulation output for each sensor class and spatial performance described above are provided. Image chips containing the features of interest listed are shown in the table below. Each image chip can be selected (double click) to open a second window with a larger, downloadable version of the image. Panchromatic image chips are provided in a following table.
## Multispectral Image Simulation Examples

<table>
<thead>
<tr>
<th>Sensor Class</th>
<th>Original Input Image</th>
<th>Blurry Q-effective = 2</th>
<th>Balanced Q-effective = 1.5</th>
<th>Aliased Q-effective = 1</th>
<th>Very Aliased Q-effective = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WorldView-3</strong>&lt;br&gt;<strong>Input GSD = 1.33 m</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Moderate Resolution Satellite</td>
<td><strong>GSD = 10 m</strong></td>
<td>RER = 0.45&lt;br&gt;FWHM = 2.0&lt;br&gt;MTF @ Nyquist = 0.03&lt;br&gt;MTF ½ Nyquist = 0.42&lt;br&gt;MTF50 = 0.22</td>
<td>RER = 0.58&lt;br&gt;FWHM = 1.5&lt;br&gt;MTF @ Nyquist = 0.015&lt;br&gt;MTF ½ Nyquist = 0.62&lt;br&gt;MTF50 = 0.30</td>
<td>RER = 0.75&lt;br&gt;FWHM = 1.0&lt;br&gt;MTF @ Nyquist = 0.40&lt;br&gt;MTF ½ Nyquist = 0.80&lt;br&gt;MTF50 = 0.44</td>
<td>RER = 0.97&lt;br&gt;FWHM = 0.5&lt;br&gt;MTF @ Nyquist = 0.8&lt;br&gt;MTF ½ Nyquist = 0.95&lt;br&gt;MTF50 = exceeds Nyquist</td>
</tr>
<tr>
<td><strong>Airport</strong></td>
<td>The runway and buildings become aliased as Q-effective decreases, however the planes and airport infrastructure become easier to discern.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Road Interchange</strong></td>
<td>When Q-effective = 2, the roads and building lose definition, and become aliased as Q-effective decreases.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>Description</td>
<td>GeoEye-1</td>
<td>Moderate Resolution Satellite</td>
<td>Agricultural Fields</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------------------------------------------------</td>
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<td></td>
</tr>
</tbody>
</table>
| Dense Urban Area      | Although aliased, lower Q-effective values may be more desirable in this case, as the streets and buildings are easier to discern. | RER = 0.45  
FWHM = 2.0  
MTF @ Nyquist = 0.03  
MTF ½ Nyquist = 0.42  
MTF50 = 0.22 | RER = 0.58  
FWHM = 1.5  
MTF @ Nyquist = 0.015  
MTF ½ Nyquist = 0.62  
MTF50 = 0.30 | RER = 0.75  
FWHM = 1.0  
MTF @ Nyquist = 0.40  
MTF ½ Nyquist = 0.80  
MTF50 = 0.44 | RER = 0.97  
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MTF @ Nyquist = 0.8  
MTF ½ Nyquist = 0.95  
MTF50 = *exceeds* Nyquist |
<p>| Agricultural Fields   | Over large fields, the blurriness at high Q-effective values is less of an issue. At Q-effective = 0.5, a Moire-like aliasing pattern (not in the input imagery) is introduced into the field. | | | | |</p>
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<th>Road</th>
<th>Leica DMCIII Aerial</th>
<th>High Resolution Satellite</th>
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<td>GSD = 1 m</td>
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<tr>
<td>Road Intersection</td>
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<td>RER = 0.45 FWHM = 2.0 MTF @ Nyquist = 0.03 MTF ½ Nyquist = 0.42 MTF50 = 0.22</td>
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<td>Urban Area</td>
<td>Q-effective = 1 and 1.5 provide definition of rooftops and cars without aliasing</td>
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MTF @ Nyquist = 0.03 MTF ½ Nyquist = 0.42 MTF50 = 0.22

MTF @ Nyquist = 0.015 MTF ½ Nyquist = 0.62 MTF50 = 0.30

MTF @ Nyquist = 0.40 MTF ½ Nyquist = 0.80 MTF50 = 0.44

MTF @ Nyquist = 0.8 MTF ½ Nyquist = 0.95 MTF50 = exceeds Nyquist
### Parking Lot
When Q-effective = 2, the lines in the parking lot cannot be differentiated. At lower Q-effective values, the lines and edges in the imagery are aliased, but individual parking spaces can be seen.

### Agricultural Fields
Lower Q-effective values provide more detail within the field however, aliasing can be observed in the fields and the road when Q-effective = 0.5.

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Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

| High Resolution Aerial | Leica DMCIII Aerial Input GSD = 0.03 m | RER = 0.45  
FWHM = 2.0  
MTF @ Nyquist = 0.03  
MTF ½ Nyquist = 0.42  
MTF50 = 0.22 | RER = 0.58  
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MTF50 = 0.44 | RER = 0.97  
FWHM = 0.5  
MTF @ Nyquist = 0.8  
MTF ½ Nyquist = 0.95  
MTF50 = exceeds Nyquist |

GSD = 0.75 m
Road Intersection

Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Homes

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.

Agricultural Fields

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

| High Resolution Aerial | Leica DMCIII Aerial Input GSD = 0.03 m | RER = 0.45  
FWHM = 2.0  
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MTF @ Nyquist = 0.015  
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MTF @ Nyquist = 0.40  
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MTF50 = 0.44 | RER = 0.97  
FWHM = 0.5  
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Road Intersection

Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Homes

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.

Agricultural Fields

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

Leica DMCIII Aerial

Input GSD = 0.03 m

- RER = 0.45
- FWHM = 2.0
- MTF @ Nyquist = 0.03
- MTF ½ Nyquist = 0.42
- MTF50 = 0.22

- RER = 0.58
- FWHM = 1.5
- MTF @ Nyquist = 0.015
- MTF ½ Nyquist = 0.62
- MTF50 = 0.30

- RER = 0.75
- FWHM = 1.0
- MTF @ Nyquist = 0.40
- MTF ½ Nyquist = 0.80
- MTF50 = 0.44

- RER = 0.97
- FWHM = 0.5
- MTF @ Nyquist = 0.8
- MTF ½ Nyquist = 0.95
- MTF50 = exceeds Nyquist

High Resolution Aerial

GSD = 0.3 m
### Road Intersection

Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

### Homes

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.

### Agricultural Fields

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

<table>
<thead>
<tr>
<th><strong>High Resolution Aerial</strong></th>
<th><strong>Leica DMCIII Aerial</strong></th>
<th><strong>Input GSD = 0.03 m</strong></th>
<th><strong>RER = 0.45</strong></th>
<th><strong>FWHM = 2.0</strong></th>
<th><strong>MTF @ Nyquist = 0.03</strong></th>
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</tbody>
</table>

GSD = 0.15 m
Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

### Panchromatic Image Simulation Examples

<table>
<thead>
<tr>
<th>Sensor Class</th>
<th>Original Input Image</th>
<th>Blurry Q-effective = 2</th>
<th>Balanced Q-effective = 1.5</th>
<th>Aliased Q-effective = 1</th>
<th>Very Aliased Q-effective = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate Resolution Satellite</td>
<td>WorldView-3</td>
<td>RER = 0.45</td>
<td>RER = 0.58</td>
<td>RER = 0.75</td>
<td>RER = 0.97</td>
</tr>
<tr>
<td>GSD = 0.33 m</td>
<td>GSD = 0.33 m</td>
<td>FWHM = 2.0</td>
<td>FWHM = 1.5</td>
<td>FWHM = 1.0</td>
<td>FWHM = 0.5</td>
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<tr>
<td></td>
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<td>MTF @ Nyquist = 0.03</td>
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<td>MTF50 = 0.22</td>
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<td>MTF50 = exceeds Nyquist</td>
</tr>
<tr>
<td>10 m</td>
<td><strong>Airport</strong></td>
<td>The runway and buildings become aliased as Q-effective decreases, however the planes and airport infrastructure become easier to discern.</td>
<td></td>
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</tr>
<tr>
<td><strong>Road Interchange</strong></td>
<td>When Q-effective = 2, the roads and building lose definition, and become aliased as Q-effective decreases.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dense Urban Area</strong></td>
<td>Although aliased, lower Q-effective values may be more desirable in this case, as the streets and buildings are easier to discern.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>GeoEye-1</strong></td>
<td><strong>Input GSD = 0.49 m</strong></td>
<td><strong>RER</strong></td>
<td><strong>FWHM</strong></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>= 0.45</td>
<td>= 2.0</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Resolution Satellite</td>
<td>GSD = 10 m</td>
<td>GSD = 1 m</td>
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<tr>
<td>Area</td>
<td>Description</td>
<td></td>
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<td>Parking Lot</td>
<td>When Q-effective = 2, the lines in the parking lot cannot be differentiated. At lower Q-effective values, the lines and edges in the imagery are aliased, but individual parking spaces can be seen.</td>
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Agricultural Fields

- Lower Q-effective values provide more detail within the field however, aliasing can be observed in the fields and the road when $Q_{\text{effective}} = 0.5$.

| High Resolution Aerial | \multicolumn{4}{c}{Leica DMCIII Aerial} |
|------------------------|-------------------------------|-----------------|-----------------|-----------------|
| GSD = 1 m              | \multicolumn{4}{c}{Input GSD = 0.03 m} |
|                        | RER = 0.45                    | RER = 0.58       | RER = 0.75       | RER = 0.97       |
|                        | FWHM = 2.0                    | FWHM = 1.5       | FWHM = 1.0       | FWHM = 0.5       |
|                        | MTF @ Nyquist = 0.03          | MTF @ Nyquist = 0.015 | MTF @ Nyquist = 0.40 | MTF @ Nyquist = 0.8 |
|                        | MTF $\frac{1}{2}$ Nyquist = 0.42 | MTF $\frac{1}{2}$ Nyquist = 0.62 | MTF $\frac{1}{2}$ Nyquist = 0.80 | MTF $\frac{1}{2}$ Nyquist = 0.95 |
|                        | MTF50 = 0.22                  | MTF50 = 0.30     | MTF50 = 0.44     | MTF50 = exceeds Nyquist |

Road Intersection

- Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Homes

- Q-effective = 1.5 and 1 provide feature definition without significant aliasing.
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<tr>
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<td><strong>High Resolution Aerial</strong></td>
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<td>Input GSD = 0.03 m</td>
<td>GSD = 0.3 m</td>
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Agricultural Fields

Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5.

Leica DMC III Aerial

- **Input GSD** = 0.03 m
- **RER** = 0.45
- **FWHM** = 2.0
- **MTF @ Nyquist** = 0.03
- **MTF ½ Nyquist** = 0.42
- **MTF50** = 0.22

- **RER** = 0.58
- **FWHM** = 1.5
- **MTF @ Nyquist** = 0.015
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- **MTF50** = *exceeds Nyquist*

High Resolution Aerial

- **GSD** = 0.15 m

Road Intersection

Although aliasing is visible at lower Q-effective values, smaller features are more easily differentiated.

Homes

Q-effective = 1.5 and 1 provide feature definition without significant aliasing.
| **Agricultural Fields** | Features within the field are more easily seen at lower Q-effective values, although aliasing is visible when Q-effective = 0.5. |
References and Further Reading


