An Automated Tool to Estimate the Spatial Resolution of Products Acquired by High Spatial Resolution Remote Sensing Imaging Systems

Mary Pagnutti
Robert E. Ryan

Joint Agency Commercial Imagery Evaluation
Civil Commercial Imagery Evaluation Workshop
Fairfax, VA
March 17, 2010
Image Formation

• An image can be considered the convolution of a point spread function (PSF) with an input scene that is sampled

\[ I_o(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_i(x', y') PSF(x'-x, y'-y) dx' dy' \]

where \( I_o(x, y) \) is the output image

\( I_i(x', y') \) is the input object

PSF is the system's impulse response and is assumed to be a slow varying function
Image Formation Example I

Input Image
20 m x 20 m Target

+

PSF
4 m FWHM

Blurred Image
20 m x 20 m Target

Sampling

GSD 1 m

GSD 2 m

GSD 4 m
Image Formation Example II

Input Image
20 m x 20 m Target

PSF
1 m FWHM

Blurred Image
20 m x 20 m Target

Sampling

GSD 1 m

GSD 2 m

GSD 4 m
Spatial Resolution Characterization Considerations

• Point Spread Function (PSF) or Optical Transfer Function (OTF) are desired but difficult to determine fully in practice
• Edge and pulse targets allow for partial evaluation of PSF and OTF
  – One dimensional evaluations
Common Spatial Resolution Metrics

Frequency Domain
• Modulation Transfer Function (MTF)
  – MTF at Nyquist typical parameter

Spatial Domain
• Relative Edge Response (RER)

![Diagram showing MTF and RER parameters](image-url)
MTF Estimation

**Edge Response**

- Differentiate

**Line Spread Function**

- Fourier Transform

**MTF**

- Nyquist frequency
GSD 20 cm
RER ~0.7

GSD 40 cm
RER ~1.0

GSD 60 cm
RER ~1.0

GSD 80 cm
RER ~1.0
Problem...

Most commonly used estimation techniques require engineered targets (deployed or fixed)
Traditional Spatial Resolution Targets

- **Fort Huachuka tri-bar target**
- **Deployable targets at the South Dakota State University site**
- **NASA SSC painted concrete radial target**
- **Causeway bridge over Lake Pontchartrain**

Digital Globe provided satellite imagery
Traditional Spatial Resolution Targets

These types of targets however, will not generally be available in the imagery to validate spatial resolution.

Digital Globe provided satellite imagery
Natural Edge Target Spatial Resolution Estimation

- Exploit features in nominal imagery
- Edge response estimation without dedicated targets
- Developing automated process
  - Identify edges
  - Construct resulting edge response
  - Calculate MTF and RER
“Natural” Edge Targets Examples

- Natural edge targets within the imagery can be used

- Street center lines (pulse targets)
- Building Shadows
- Rooflines
Automated Spatial Resolution
Algorithm Flowchart

1. **Image**
   - Sobel edge detection returns points where gradient of image is maximum.

2. **Edge Detection**
   - Signal-to-Noise Ratio of near horizontal or near vertical edges

3. **Edge Screening**
   - Edges plotted and curve-fit using LOESS or Sigmoidal functions. Curves are set to even spacing.

4. **Edge Response**
   - Smoothed edge response is differentiated to estimate LSF. Fourier transform of LSF gives MTF at Nyquist

5. **MTF Estimation**
   - Difference of edge response at +/-0.5 pixel.

6. **RER Estimation**
Finding Edges and Generating Edge Response

- Algorithm developed for automated edge detection and analysis using scene data

Simulated image with noise

Edge found with Sobel method

Data points across the edge to estimate edge response
Natural Edges at SSC
Edge Response Processing Option I

- Parametric
  - Edge response is fitted to a function whose characteristic shape is “representative” of the measured edge
  - Addresses SNR associated with numerical derivative of edge response
  - Sigmoidal function or superposition of Sigmoidal functions commonly used
    - Previous SSC work used superposition of several Sigmoidal functions to account for MTFC ringing
  - Can breakdown at low MTF@Nyquist values
Parametric Sigmoidal Function

\[ S(x) = \frac{a}{1 + \exp \left( \frac{x - b}{c} \right)} \]
Parametric Sigmoidal Function (cont.)

**Sigmoidal Function LSF**

- Blue line: RER=0.24 FWHM = 3.5
- Green line: RER=0.46 FWHM = 1.8
- Red line: RER=0.76 FWHM = 0.88

**Sigmoidal Function MTF**

- Blue line: RER=0.24 MTF@Nyquist = 0.0025
- Green line: RER=0.46 MTF@Nyquist = 0.1
- Red line: RER=0.76 MTF@Nyquist = 0.49

**Legend:**
- LSF: Linear Spatial Frequency
- MTF: Modulation Transfer Function
- Pixel
- Normalized Frequency Pixel$^{-1}$
Sigmoidal Fit Example

**Edge Response**

![Edge Response Graph]

**Normalized LSF**

![Normalized LSF Graph]

**Residuals**

![Residuals Graph]

**MTF**

![MTF Graph]

- **SNR = 40.57**
- **Max DN = 783**
- **Min DN = 346**
Edge Response Processing Option II

- Non-parametric
  - Minimal assumptions about underlying edge response shape
- Local Weighted Regression (LOWESS or LOESS)
  - Smoothes curve and produces an equally distributed sampling for FFT processing
  - Only partially addresses the SNR issues associated with taking numerical derivatives
LOESS Example

Edge Response

Normalized LSF

Residuals

MTF

Max DN = 783
Min DN = 346
Validation

- Used several years of IKONOS and Quickbird SSC tarp data to estimate MTF and RER using automated algorithm and comparing results with traditional method.
Comparison of Automated Method with SSC Traditional Methods

RER comparisons using tarp edge

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Processing</th>
<th>Date</th>
<th>Location</th>
<th>Orientation</th>
<th>Tarp RER</th>
<th>LOESS</th>
<th>SIG</th>
<th>% Diff (L)</th>
<th>% Diff (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKONOS</td>
<td>MTFC Off/CC</td>
<td>1/15/2002</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
<td>-0.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2/17/2002</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.54</td>
<td>0.55</td>
<td>0.54</td>
<td>-1.6%</td>
<td>-0.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/22/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.46</td>
<td>0.45</td>
<td>0.47</td>
<td>1.5%</td>
<td>-1.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12/15/2004</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.47</td>
<td>0.47</td>
<td>0.49</td>
<td>0.6%</td>
<td>-4.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/24/2005</td>
<td>Wiggins</td>
<td>Easting</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
<td>0.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4/15/2005</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.49</td>
<td>0.48</td>
<td>0.48</td>
<td>2.0%</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>MTFC Off/NN</td>
<td>7/22/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.43</td>
<td>0.42</td>
<td>0.44</td>
<td>1.5%</td>
<td>-1.3%</td>
</tr>
<tr>
<td>QuickBird</td>
<td>CC</td>
<td>7/20/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.56</td>
<td>0.54</td>
<td>0.55</td>
<td>4.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8/25/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.0%</td>
<td>-0.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9/7/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.58</td>
<td>0.54</td>
<td>0.55</td>
<td>6.4%</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11/14/2002</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.53</td>
<td>0.50</td>
<td>0.55</td>
<td>6.0%</td>
<td>-4.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9/15/2003</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.51</td>
<td>0.49</td>
<td>0.49</td>
<td>4.0%</td>
<td>3.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/10/2004</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.53</td>
<td>0.52</td>
<td>0.56</td>
<td>2.4%</td>
<td>-4.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/12/2005</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>-0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/22/2005</td>
<td>Brookings</td>
<td>Northing</td>
<td>0.51</td>
<td>0.48</td>
<td>0.52</td>
<td>5.7%</td>
<td>-2.8%</td>
</tr>
</tbody>
</table>
Comparison of Automated Method with SSC Traditional Methods

MTF at Nyquist comparisons using tarp edge

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Processing</th>
<th>Date</th>
<th>Location</th>
<th>Orientation</th>
<th>Tarp MTF</th>
<th>LOESS</th>
<th>SIG</th>
<th>% Diff (L)</th>
<th>% Diff (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKONOS</td>
<td>MTFC Off/CC</td>
<td>1/15/2002</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.13</td>
<td>0.13</td>
<td>0.10</td>
<td>-1.1%</td>
<td>19.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2/17/2002</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.18</td>
<td>0.20</td>
<td>0.14</td>
<td>-10.8%</td>
<td>22.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/22/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.07</td>
<td>0.11</td>
<td>0.07</td>
<td>-58.2%</td>
<td>-6.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12/15/2004</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.14</td>
<td>0.09</td>
<td>0.09</td>
<td>34.5%</td>
<td>33.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/24/2005</td>
<td>Wiggins</td>
<td>Easting</td>
<td>0.14</td>
<td>0.12</td>
<td>0.12</td>
<td>16.5%</td>
<td>12.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4/15/2005</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.14</td>
<td>0.10</td>
<td>0.08</td>
<td>30.6%</td>
<td>39.3%</td>
</tr>
<tr>
<td></td>
<td>MTFC Off/NN</td>
<td>7/22/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.12</td>
<td>0.09</td>
<td>0.05</td>
<td>21.5%</td>
<td>54.8%</td>
</tr>
<tr>
<td>QuickBird</td>
<td>CC</td>
<td>7/20/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
<td>1.1%</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8/25/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
<td>11.0%</td>
<td>11.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9/7/2002</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.21</td>
<td>0.15</td>
<td>0.15</td>
<td>27.8%</td>
<td>28.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11/14/2002</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.15</td>
<td>0.03</td>
<td>0.15</td>
<td>79.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9/15/2003</td>
<td>Brookings</td>
<td>Easting</td>
<td>0.14</td>
<td>0.14</td>
<td>0.09</td>
<td>-1.0%</td>
<td>34.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/10/2004</td>
<td>Stennis</td>
<td>Easting</td>
<td>0.14</td>
<td>0.07</td>
<td>0.15</td>
<td>47.1%</td>
<td>-8.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/12/2005</td>
<td>Stennis</td>
<td>Northing</td>
<td>0.14</td>
<td>0.13</td>
<td>0.12</td>
<td>4.3%</td>
<td>17.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/22/2005</td>
<td>Brookings</td>
<td>Northing</td>
<td>0.06</td>
<td>0.06</td>
<td>0.12</td>
<td>-1.3%</td>
<td>-102.5%</td>
</tr>
</tbody>
</table>
Validation Study Summary

- Algorithm produce similar results as traditional SSC approach using tarp targets
- RER and MTF @ Nyquist results comparable with high contrast target

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Traditional Method</th>
<th>LOESS</th>
<th>Sigmoidal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MTF</td>
<td>RER</td>
<td>MTF</td>
</tr>
<tr>
<td>IKONOS</td>
<td>0.15±0.04</td>
<td>0.54±0.03</td>
<td>0.11±0.05</td>
</tr>
<tr>
<td>MTFC Off/CC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QuickBird</td>
<td>0.13±0.04</td>
<td>0.50±0.03</td>
<td>0.13±0.04</td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
New York City Imagery Example

IKONOS Imagery acquired 5/31/2001
# NYC Example

<table>
<thead>
<tr>
<th>Location</th>
<th>LOESS</th>
<th>Sigmoidal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MTF</td>
<td>RER</td>
</tr>
<tr>
<td>r01c10e1s1</td>
<td>0.09</td>
<td>0.42</td>
</tr>
<tr>
<td>r06c07e1s1</td>
<td>0.31</td>
<td>0.63</td>
</tr>
<tr>
<td>r06c11e1s1</td>
<td>0.16</td>
<td>0.44</td>
</tr>
<tr>
<td>r07c13e1s1</td>
<td>0.22</td>
<td>0.56</td>
</tr>
<tr>
<td>r08c04e1s1</td>
<td>0.28</td>
<td>0.58</td>
</tr>
<tr>
<td>r08c08e1s1</td>
<td>0.14</td>
<td>0.47</td>
</tr>
<tr>
<td>r08c22e1s1</td>
<td>0.06</td>
<td>0.32</td>
</tr>
<tr>
<td>r09c14e1s1</td>
<td>0.34</td>
<td>0.68</td>
</tr>
<tr>
<td>r09c14e2s1</td>
<td>0.29</td>
<td>0.59</td>
</tr>
<tr>
<td>r12c08e1s1</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td><strong>mean</strong></td>
<td>0.23</td>
<td>0.53</td>
</tr>
<tr>
<td><strong>stddev</strong></td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Summary

• Automated tool finds edges and estimates spatial resolution
• MTF and RER has been tested and validated
• Many edges are needed to produce good results
• Error and uncertainty analysis need to be developed