On-orbit Modulation Transfer Function (MTF) Measurements for IKONOS and QuickBird

Civil Commercial Imagery Evaluation Workshop
3/15/2006

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Outline

• Introduction
• Techniques
• Target/Site Description
• Results
  – Ikonos
  – Quickbird
• Conclusions

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This work was supported by NASA grant NNS04AB66C
Introduction

- **Point Spread Function**
  - A method of evaluating the spatial resolution of an imaging system.
  - A measure of the spread of a single point of light.

- **Modulation Transfer function (MTF)**
  - MTF is a measure of the spatial frequency response.
  - MTF is often calculated from the point spread function (PSF).
  - System response at the Nyquist frequency (or 0.5 cycle/pixel) is often used as a figure of merit.
\[ H(\omega_x, \omega_y) = \mathcal{F}\{\text{PSF}(x, y)\} \]

\[ MTF(\omega_x, \omega_y) = \frac{|H(\omega_x, \omega_y)|}{|H(0,0)|} \]

- 2-dimensional PSF and MTF are difficult to obtain.
- Often 1 dimensional functions are used:
  - 1-D PSF is the line spread function (LSF).
  - LSF can be obtained by differentiation of the edge spread function (ESF).
Techniques

- **Edge Method**
  - Sub-pixel edge locations were found by Fermi function fit.
  - A least-square error line was calculated through the edge locations.
  - Modified Savitzky-Golay filtering was applied on each line.
  - The filtered profile was differentiated to obtain LSF.
  - MTF calculated by applying Fourier transform to LSF.
• Pulse method
  – A pulse input is given to the imaging system.
  – Output of the system is the resulting image.
  – Edge detection and mSG filtering was applied to obtain output profile.
  – Take Fourier transform of the input and output.
  – MTF is calculated by dividing output by input and normalizing DC component to unity.
SNR Definition

\[
\text{SNR} = \frac{\text{DN difference}}{(\text{STD}_{\text{bright}} + \text{STD}_{\text{dark}}) / 2}
\]

\[
\text{SNR} = \frac{\text{DN difference}}{\text{STD}_{\text{background}}}
\]
Target Description

Field Plan
Field campaign pictures on 6-22-2005
• **NASA Stennis Tarp Target**
  – Radiometrically and spectrally stable target with a large DN difference from 3.6% and 52.1% reflectance panels.
  – Edge oriented to obtained sub-sampled edge profile.
  – Blue tarps oriented at same angle.
## IKONOS Acquisitions

### IKONOS Scene Information

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Targets</th>
<th>Resampling or MTF processing</th>
<th>Product Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1/2005</td>
<td>IKONOS</td>
<td>Stennis tarps</td>
<td>CC / MTFC On</td>
<td>Standard Geometrically Corrected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blue tarps</td>
<td>CC / MTFC Off</td>
<td>Standard Geometrically Corrected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mirrors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Sensor</td>
<td>Band</td>
<td>Product</td>
<td>Target</td>
</tr>
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</tr>
<tr>
<td>8/1/2005</td>
<td>IKONOS</td>
<td>Pan.</td>
<td>CC/MTF off</td>
<td>Stennis</td>
</tr>
</tbody>
</table>

**Test Image**
- Angle = 5.404 [deg]
- Sub-pixel edge location
- Least square error line

**mSG filtering with raw data**
- DN$_{diff}$ = 1040.92
- STD$_{ave}$ = 11.25
- SNR = 92.54

**Trimmed LSF**
- FWHM = 1.6226 [Pixel]

**MTF**
- Value at Nyquist = 0.1117
**Date** | **Sensor** | **Band** | **Product** | **Target** | **Elevation** | **Azimuth**  
---|---|---|---|---|---|---  
8/1/2005 | IKONOS | Pan. | CC/MTF on | Stennis | 66.0 | 118.7

- **Angle** = 5.384 [deg]

- **SNR** = 80.74

- **DN** = 1043.96

- **STD** = 12.93

- **MTF**

  - Value at Nyquist = 0.4983

- **FWHM** = 1.1322 [Pixel]

- **Trimmed LSF**

- **mSG filtering**
Angle = 5.112 [deg]

Fermi edge location
Least square error line

Modified S-Golay interpolation with raw data

DN = 629.36
SNR = 77.03

Trimmed LSF

FWHM = 3.0169 [Pixel]

Fourier transform of input and output

MTF from Continuous Input

Value at Nyquist = 0.3745
<table>
<thead>
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<th>Date</th>
<th>Sensor</th>
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<th>Target</th>
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<th>Azimuth</th>
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<tr>
<td>8/1/2005</td>
<td>IKONOS</td>
<td>Blue</td>
<td>CC/MTF on</td>
<td>Blue tarp</td>
<td>66.0</td>
<td>118.7</td>
</tr>
</tbody>
</table>

- **Modified S-Golay interpolation with raw data**
  - Raw data
  - Modified S-Golay filtering

- **Trimmed LSF**
  - Normalized Differentiation value

- **Fourier transform of input and output**
  - Discrete Output
  - Discrete Input

- **MTF from Continuous Input**
  - Normalized MTF value
  - Value at Nyquist = 0.5207
Multi-year IKONOS Comparison

- Consistent FWHM: 1.61 +/- 0.08
- Values at Nyquist frequency were very stable.
  - Mean = 0.11, STD = 0.01
- No trends in PSF/MTF over 5 years.

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<th>Sensor</th>
<th>Band</th>
<th>Product</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1/05, 7/22/02, 9/26/01, 8/5/01, 6/22/01, 5/31/01, 3/26/00</td>
<td>IKONOS</td>
<td>Pan.</td>
<td>CC/MTFC off</td>
<td>Stennis / Big Springs</td>
</tr>
</tbody>
</table>
IKONOS SDSU campus on 8/1/2005

CC With MTFC

CC Without MTFC

Noisier & Sharper than CC
IKONOS Summary

• Very consistent, high-quality sensor
  – Pan FWHM = 1.61 +/- 0.08
  – Pan MTF @ Nyquist = 0.11 +/- 0.01
  – Multispectral MTF @ Nyquist = 0.52 (2005 data)

• ‘MTFC on’ processing provides increased MTF response with typical trade-off of increased contrast with some additional noise in Pan, less in Blue band.
  – Pan FWHM = 1.08 +/- 0.10
  – Pan MTF @ Nyquist = 0.48 +/- 0.08

• No indication of sensor degradation in five years.
## Quickbird Acquisitions

- **Quickbird scene information**

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Targets</th>
<th>Resampling or MTF processing</th>
<th>Product Type</th>
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<tr>
<td>8/30/2004</td>
<td>Quickbird</td>
<td>Blue tarps</td>
<td>Resampling Kernel = CC</td>
<td>Standard2A (Radiometrically corrected)</td>
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<td></td>
<td>Mirrors</td>
<td>MTF</td>
<td></td>
</tr>
<tr>
<td>10/5/2004</td>
<td>Quickbird</td>
<td>Blue tarps</td>
<td>CC</td>
<td>Standard2A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mirrors</td>
<td>MTF</td>
<td></td>
</tr>
<tr>
<td>6/22/2005</td>
<td>QuickBird</td>
<td>Vertical Stennis</td>
<td>CC</td>
<td>Standard2A</td>
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<tr>
<td></td>
<td></td>
<td>tarps Blue tarps</td>
<td>MTF</td>
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<td></td>
<td>Mirrors</td>
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<tr>
<td>10/18/2005</td>
<td>QuickBird</td>
<td>Stennis tarps</td>
<td>MTF</td>
<td>Standard2A</td>
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<td></td>
<td></td>
<td>Blue tarps</td>
<td>CC</td>
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<tr>
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<td>Pan.</td>
<td>CC</td>
<td>Stennis</td>
</tr>
</tbody>
</table>

Test image

Sub-pixel edge location

Least square error line

mSG filtering with raw data

\[ \text{DN}_{\text{diff}} = 1038.19 \]
\[ \text{STD}_{\text{ave}} = 10.02 \]
\[ \text{SNR} = 103.62 \]

Trimmed LSF

\[ \text{FWHM} = 1.8939 \text{ [Pixel]} \]

MTF

\[ \text{Value at Nyquist} = 0.0364 \]
<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
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<th>Target</th>
<th>Elevation</th>
<th>Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/22/2005</td>
<td>Quickbird</td>
<td>Pan.</td>
<td>MTF</td>
<td>Stennis along</td>
<td>88.2</td>
<td>75.9</td>
</tr>
</tbody>
</table>

Along-track Stennis tarp target MTF result of QuickBird on 6/22/2005 (MTF)
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>6/22/2005</td>
<td>Quickbird</td>
<td>Blue</td>
<td>CC</td>
<td>Blue tarp cross</td>
<td>88.2</td>
<td>75.9</td>
</tr>
</tbody>
</table>
**Table:**

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<th>Azimuth</th>
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<tbody>
<tr>
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<td>Quickbird</td>
<td>Blue</td>
<td>MTF</td>
<td>Blue tarp cross</td>
<td>88.2</td>
<td>75.9</td>
</tr>
</tbody>
</table>

**Graphs:**

1. **Test image**
   - Angle = 5.699 \(\text{[deg]}\)
   - Fermi edge location
   - Least square error line

2. **Modified S-Golay interpolation with raw data**
   - DN
   - STD ave = 6.75
   - SNR = 112.84

3. **Trimmed LSF**
   - FWHM = 2.0699 \(\text{[Pixel]}\)

4. **Fourier transform of input and output**
   - Input
   - Output

5. **Continuous Fourier transform**
   - Discrete Output
   - Continuous Input

6. **MTF from Continuous Input**
   - Value at Nyquist = 0.2306
QuickBird panchromatic band Along / Cross Track Direction Comparison

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Band</th>
<th>Resampling</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/22/05, 10/18/05</td>
<td>Quickbird</td>
<td>Pan.</td>
<td>MTF / CC</td>
<td>Stennis</td>
</tr>
</tbody>
</table>

- First estimate of along-track PSF/MTF.
- Along-track PSF/MTF not significantly different than cross-track.
QuickBird Blue Band Along / Cross Track Direction Comparison

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Band</th>
<th>Resampling</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/22/05, 10/18/05</td>
<td>Quickbird</td>
<td>Blue</td>
<td>CC only</td>
<td>Blue tarps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cross / along-track</td>
</tr>
</tbody>
</table>

- Cross-track profile exhibits narrower PRF FWHM and under shoots.
- System MTF shape differs in the orthogonal directions.
QuickBird Blue Band Along / Cross Track Direction Comparison

- FWHM values were reduced by MTF resampling process.
- MTF values were increased—most significantly in cross track direction.

<table>
<thead>
<tr>
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<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Blue</td>
<td>MTF only</td>
<td>Blue tarps</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cross / along-track</td>
</tr>
</tbody>
</table>

PRF plots for QuickBird on 6/22/05 and 10/18/05 with MTF resampled scenes:
- 6/22/05 Cross-T. FWHM = 2.0699 [pixel], SNR = 112.8
- 10/18/05 Cross-T. FWHM = 2.0988 [pixel], SNR = 86.1
- 6/22/05 Along-T. FWHM = 2.2864 [pixel], SNR = 33.3
- 10/18/05 Along-T. FWHM = 2.2398 [pixel], SNR = 44.4

MTF plots for QuickBird on 6/22/05 and 10/18/05 with MTF resampled scenes:
- 6/22/05 Cross-T. MTF = 0.2306
- 10/18/05 Cross-T. MTF = 0.2070
- 6/22/05 Along-T. MTF = 0.2729
- 10/18/05 Along-T. MTF = 0.2153
## Quickbird Results Summary 2004-2005

<table>
<thead>
<tr>
<th>Band</th>
<th>Resamp.</th>
<th>Scan Direction</th>
<th>FWHM (gsd)</th>
<th>MTF at Nyquist (cycles/gsd)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mean</td>
<td>sigma</td>
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</tr>
<tr>
<td>Pan.</td>
<td>CC</td>
<td>Cross</td>
<td>1.89</td>
<td>0.09</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Along</td>
<td>1.89</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>MTF</td>
<td>Cross</td>
<td>1.71</td>
<td>0.26</td>
<td>1</td>
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<tr>
<td></td>
<td></td>
<td>Along</td>
<td>1.69</td>
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<td>1</td>
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<tr>
<td>Blue</td>
<td>CC</td>
<td>Cross</td>
<td>2.32</td>
<td>0.01</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Along</td>
<td>2.49</td>
<td>0.01</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>MTF</td>
<td>Cross</td>
<td>2.11</td>
<td>0.05</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Along</td>
<td>2.27</td>
<td>0.02</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes:
1. Blue Band FWHM’s are for Pulse Response Functions.
2. Only one Pan band observation! Essentially same PSF/MTF in both scan directions.
3. MTF resampling provides noticeable contrast improvement; SNR is lowered, but still acceptable.
4. Overall SNR is good to excellent.
5. PRF is very repeatable in Blue band; MTF is noticeably less so
Quickbird SDSU campus on 6/22/2005

MTF resampling

CC resampling

Noisier & Sharper than CC
### 2002/2003/2005 QuickBird Comparisons

<table>
<thead>
<tr>
<th>Date</th>
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</tr>
</thead>
<tbody>
<tr>
<td>7/20/02, 8/25/02, 9/7/02, 9/15/03, 10/18/05</td>
<td>Quickbird</td>
<td>Pan.</td>
<td>CC</td>
<td>Stennis tarp</td>
</tr>
</tbody>
</table>

- GSD changed from 0.7 to 0.6 meters after 2003.
- Spatial resolution performance appears consistent from 2002 to 2005.

![Normalized LSF](image1)

![Normalized MTF](image2)

<table>
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### Graphs

- **Normalized LSF**
  - Colors and markers represent different dates and FWHM, SNR values.
  - Y-axis: Normalized LSF
  - X-axis: Meters

- **Normalized MTF**
  - Colors and markers represent different dates and MTF values.
  - Y-axis: Normalized MTF
  - X-axis: Normalized frequency [cycle/meter]
Overall Quickbird Conclusions

- Initial along-scan PSF/MTF estimates indicate slightly more blur than cross-scan, as expected.
- Good to excellent SNR.
- MTF compensation provides noticeable contrast boost with normal loss of SNR in Panchromatic band, but minimal loss of SNR in Blue band.
- No degradation of Panchromatic band PSF/MTF indicated from 2002 through 2005.