Spatial Resolution Characterization for QuickBird Image Products 2003-2004 Season

Slawomir Blonski
Science Systems and Applications, Inc.
John C. Stennis Space Center, Mississippi

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Presentation Outline

- Data measurements and analysis
  - SSC edge target deployment
  - Edge response extraction and modeling
- Multiple results for QuickBird panchromatic images resampled with Cubic Convolution (CC) and Modulation Transfer Function (MTF) compensation kernels
- Discussion of results for CC images: model MTF
- Relative Edge Response (RER) measurements for CC and MTF images
  - RER interpretation in remote sensing
- Summary of the results

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SSC Edge Target

- Formed from two high-contrast tarps: nominally 3.5% and 52% reflectance, 20 m × ~21 m each
- Deployed by a NASA ground-support team near NOAA's data buoy facility at Stennis Space Center or by the SDSU team at Brookings, South Dakota

Early morning deployment of the edge target tarps at Stennis Space Center, Mississippi

QuickBird multispectral image acquired on January 10, 2004
GSD = 2.4 m

Selecting Edge Response Data

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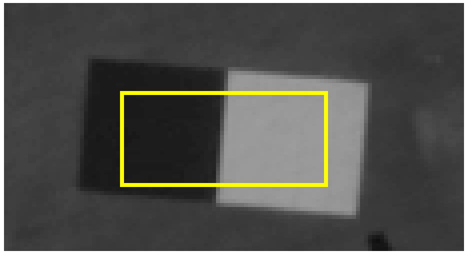
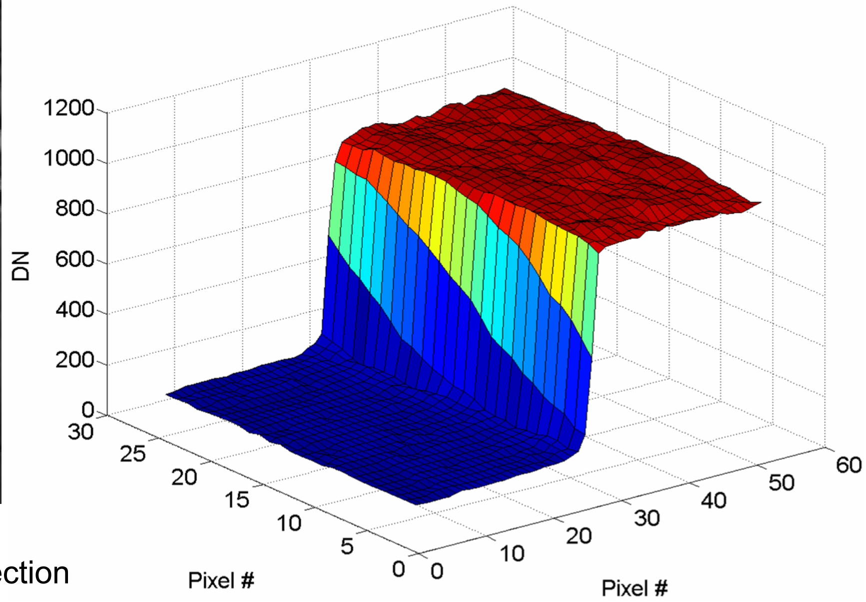
QuickBird panchromatic image acquired on January 10, 2004
GSD = 60 cm; Edge target tarps oriented for testing in the easting direction

Image area selected for edge response analysis



zoom 2×

A set of shifted edge response data lines ready for analysis



Fitting Analytical Functions

$$e_i(x) = d + \sum_{k=1}^{N} \frac{a_k}{1 + \exp\left(\dfrac{\alpha \Delta i + b_k - x}{c_k}\right)}$$

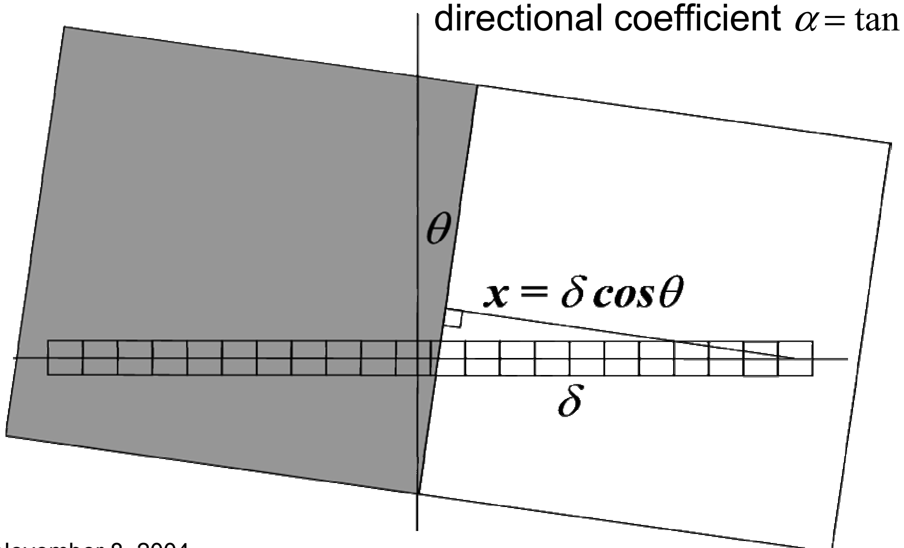
New approach in 2004 (also used in USGS digital camera characterizations): The nonlinear least-squares optimization with superposition of N sigmoidal functions is conducted seven times for N = 3, 5, 7, 9, 11, 13, and 15. The value of N that provides the best fit is selected to generate final results.

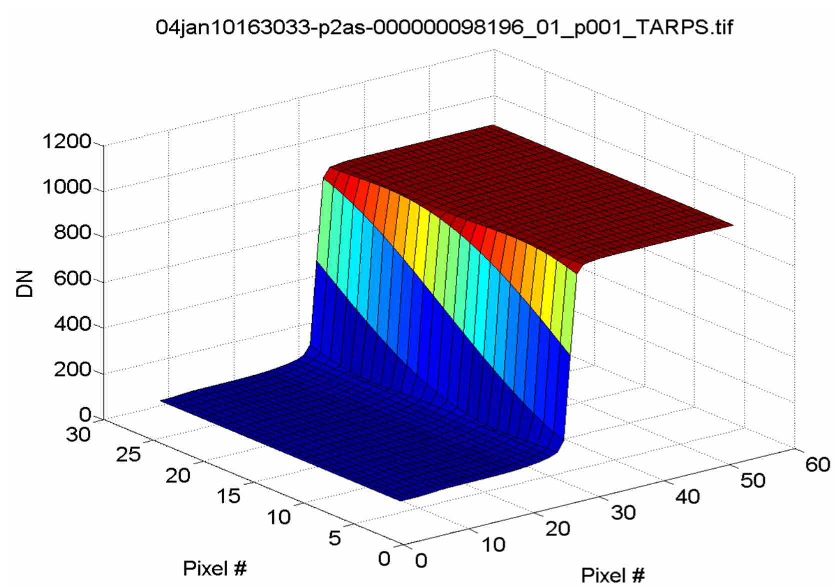
Optimized parameters:

- α, d
- a_k, b_k, c_k, k = 1, …, N

With no restrictions placed on values of the optimization parameters, the sigmoidal functions assume a role of general approximation functions (as in *neural networks*).

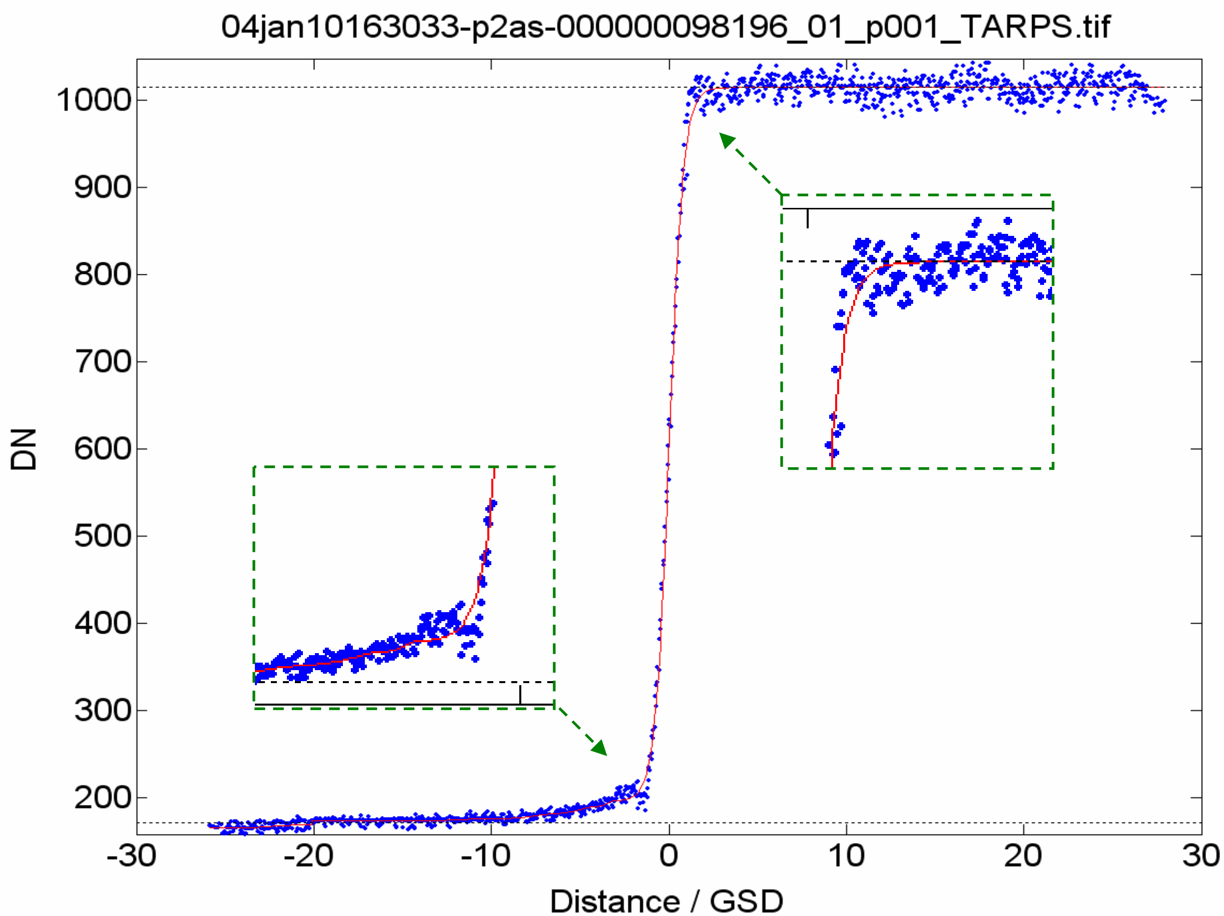
All edge positions are on a straight line given by the equation $\alpha\Delta i + b_k$. Difference in the edge position is introduced by the edge response index (i) multiplied by image GSD (Δ) and directional coefficient $\alpha = \tan\theta$.



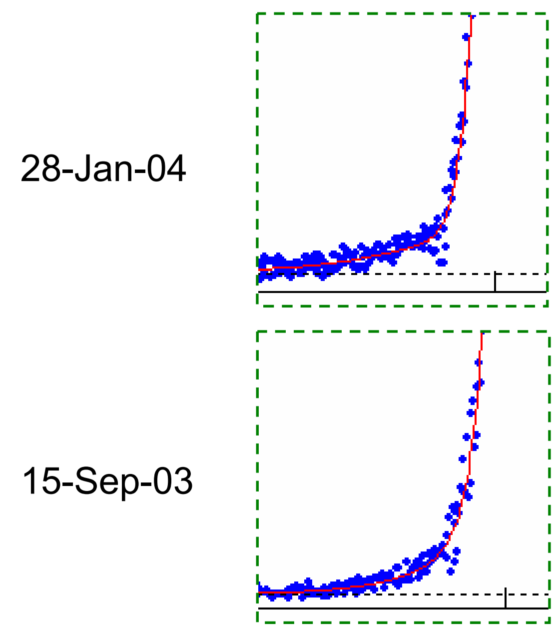


Edge Response for CC Images

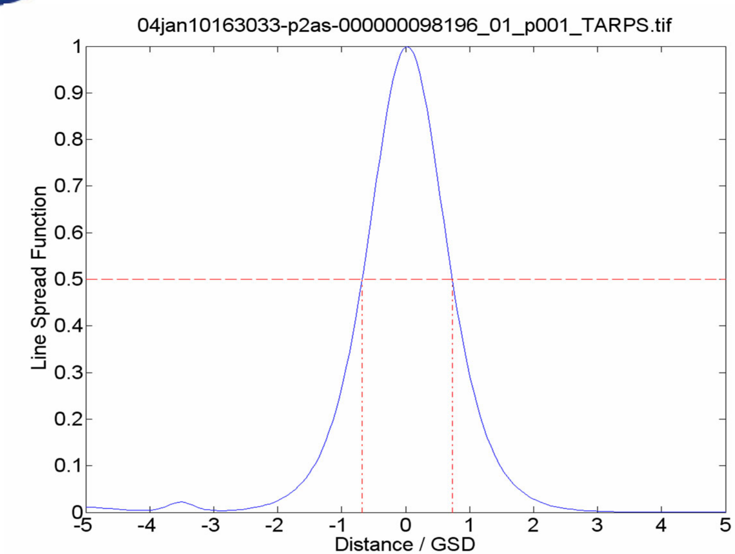
For each cubic-convolution (CC) image, the edge response analysis was conducted multiple times. The main graph shows the edge response that was most often obtained for the CC images: generally a good approximation, but small features omitted – not very accurate result – the analytical function diverges from the image data near the edge response bend points (see graph inserts).



Similar features are also present in edge responses extracted from other images processed with CC resampling:

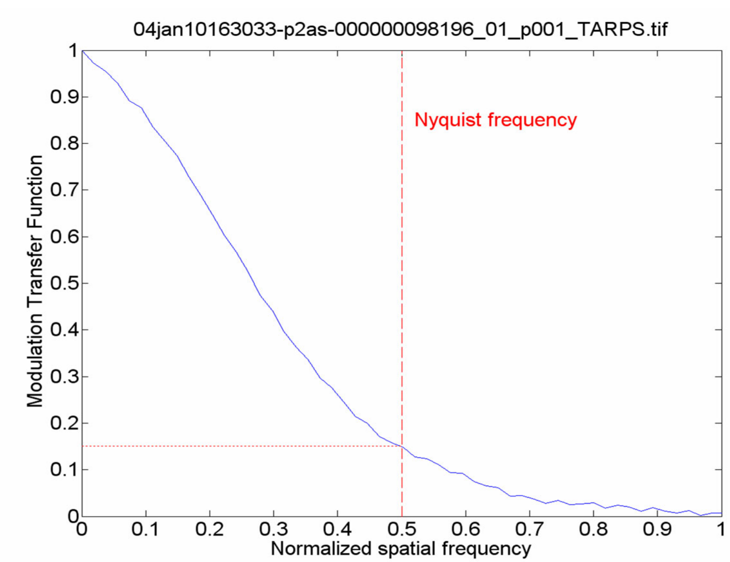


LSF and MTF for CC Images



Line Spread Function (LSF) derived by numerical differentiation from the smooth analytical function obtained as the most-often result of the edge response analysis has a simple, Gaussian/Lorentzian shape.

Full Width at Half Maximum (FWHM) of LSF is approximately equal to 1.4 GSD.



Modulation Transfer Function (MTF) obtained by Fourier transform of the LSF also has a Gaussian-like shape.

The value of MTF at the Nyquist spatial frequency (half the sampling rate) is approximately equal to 0.15.

Edge Response for One CC Image

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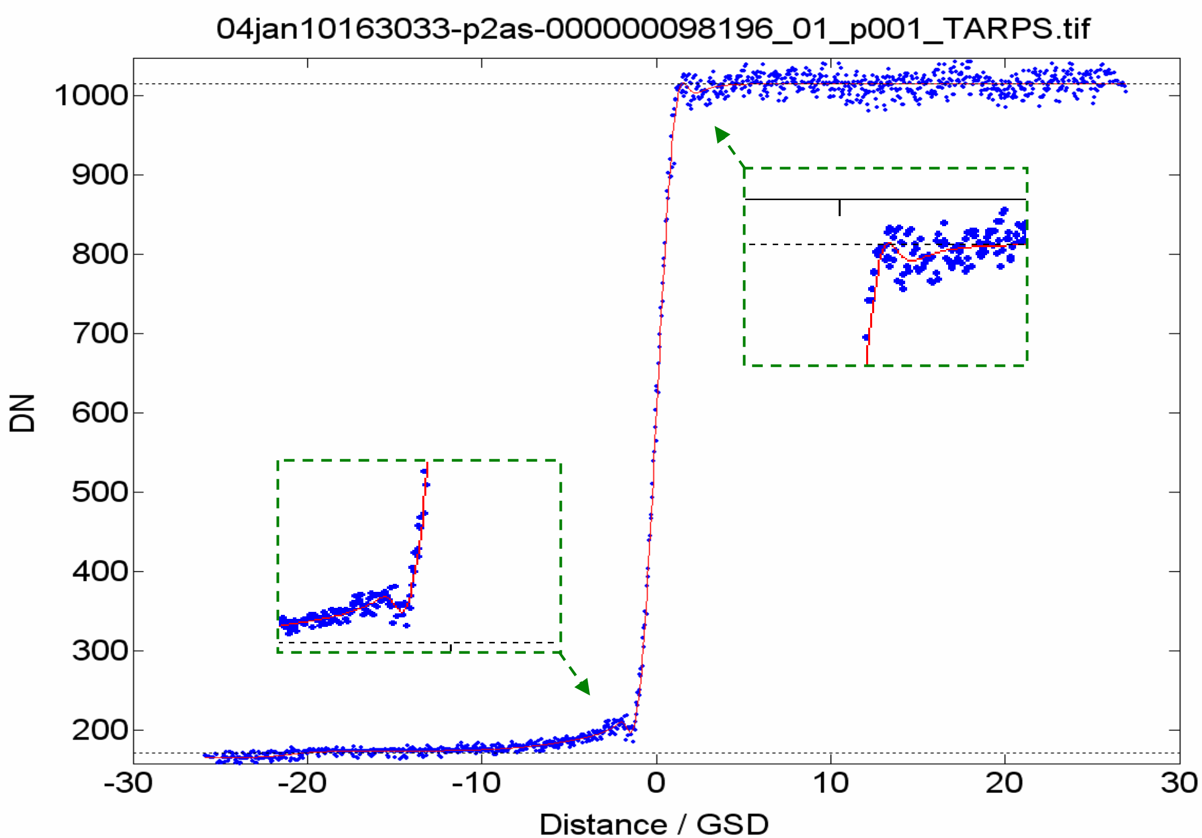
In some cases for one CC image, the edge response analysis leads to a better result. This is generally a good approximation as well, but it is even better because the small features are included. More accurate result: the analytical function more closely follows the image data near the edge response bend points (see graph inserts).

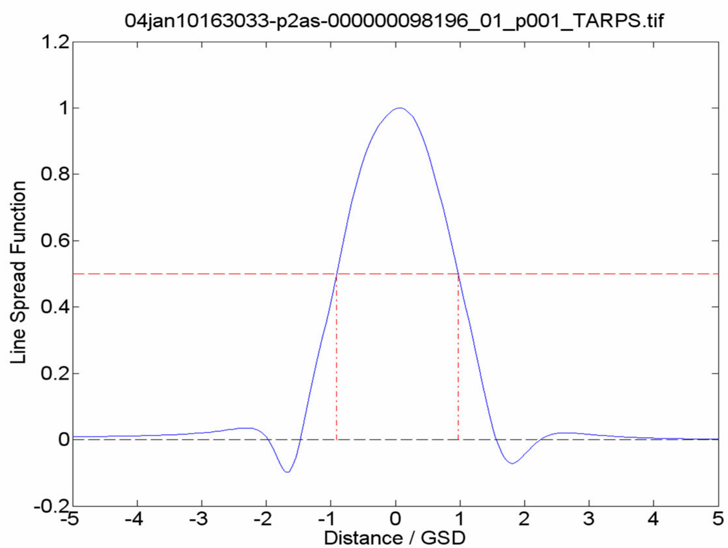


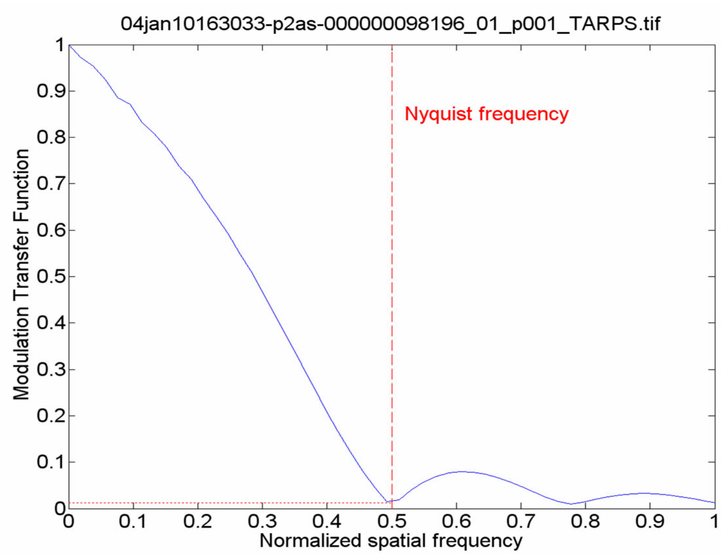
For the same image, the same analysis procedure generates two different results: this one better.

The edge response analyses differ only slightly by selected image areas, but this drives the curve fitting to very different minima.

Although this result is not obtained as often as the one presented on preceding slides, it is reproducible for this image.

LSF and MTF for One CC Image





The LSF is quite broad and has a trapezoidal shape modified by the small features.

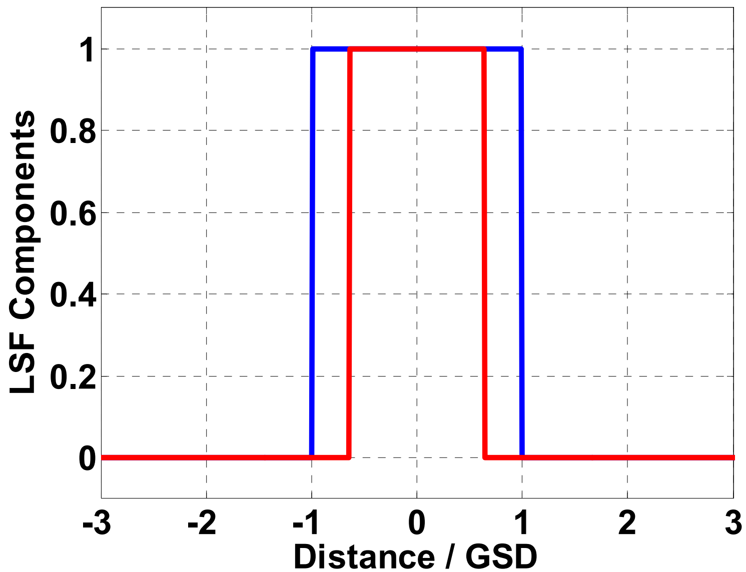
FWHM of LSF is approximately equal to 1.9 GSD.

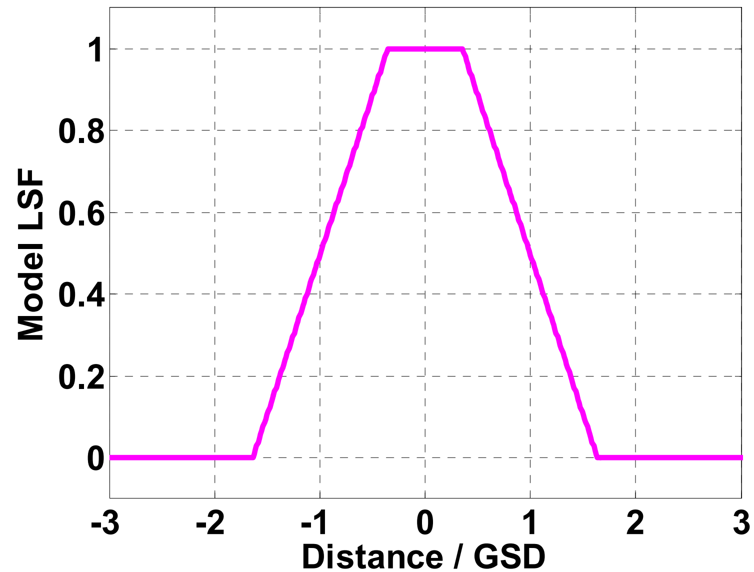
The MTF resembles a product of two *sinc* functions with a node at the Nyquist frequency and another node close to 0.8 of the sampling frequency.

The value of MTF at the Nyquist frequency seems to be equal to 0 (zero).

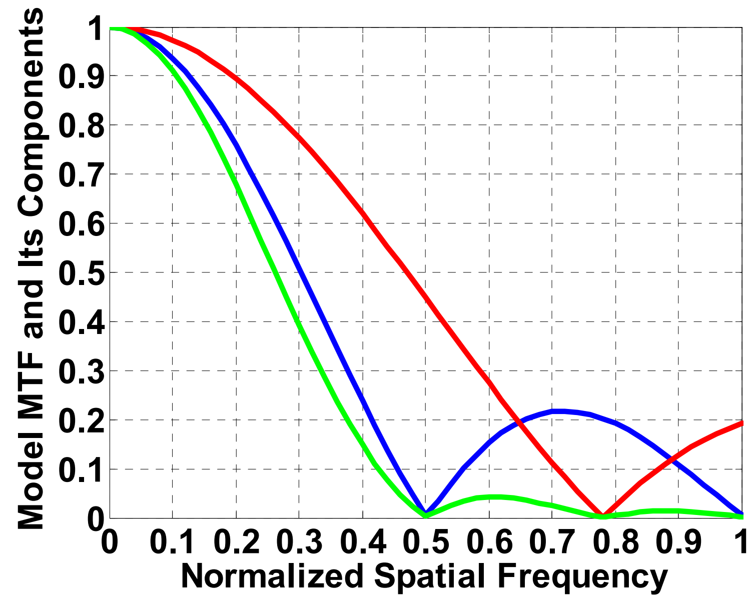
That the Fourier transformation of a combination of sigmoidal function derivatives produces a function of this shape is the most unexpected outcome and is a strong argument for correctness of the analysis.

Simple Model of LSF and MTF



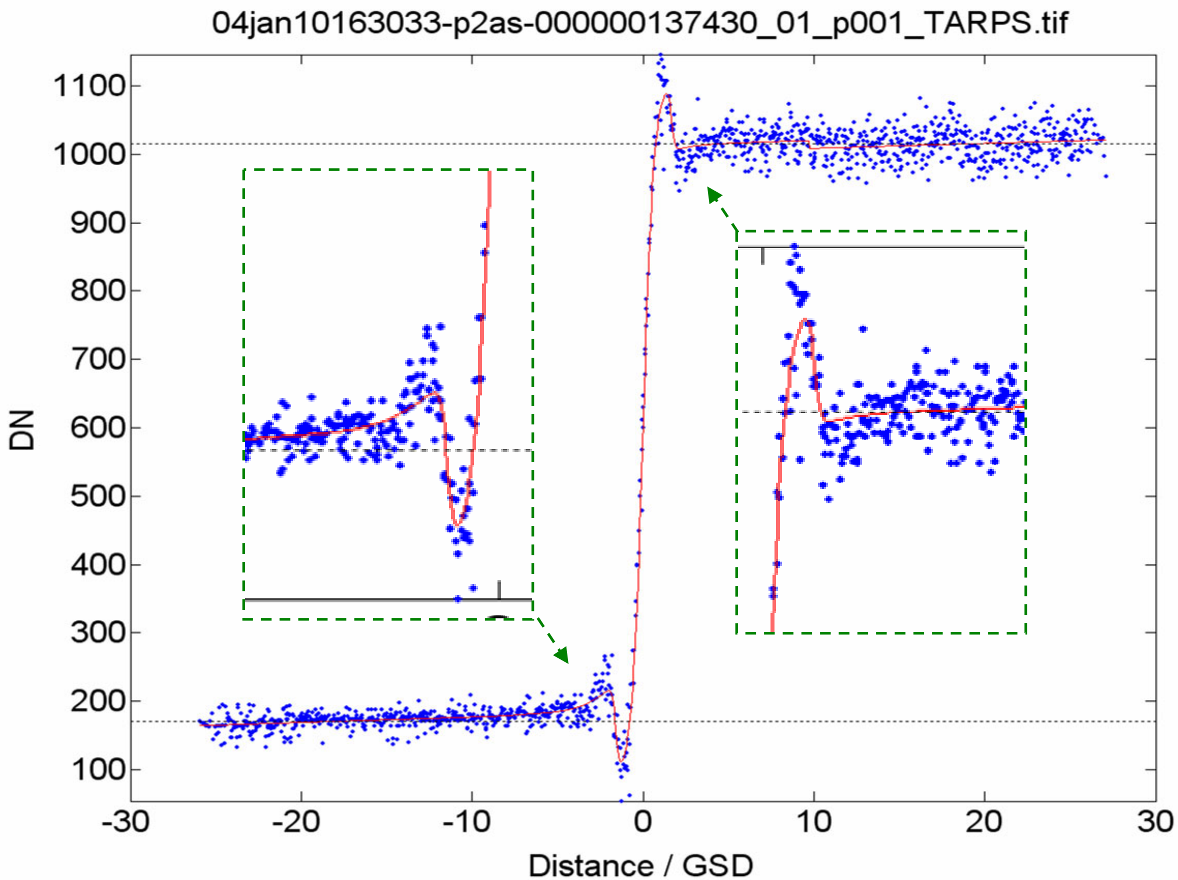


In the spatial domain, the product of the *sinc* functions (green) transforms into a convolution of two box functions with widths equal to 2 (blue) and ~1.3 (red) GSD. The convolution results in a trapezoidal function (magenta) with mean length of the bases equal to twice the GSD.



Edge Response for MTF Image

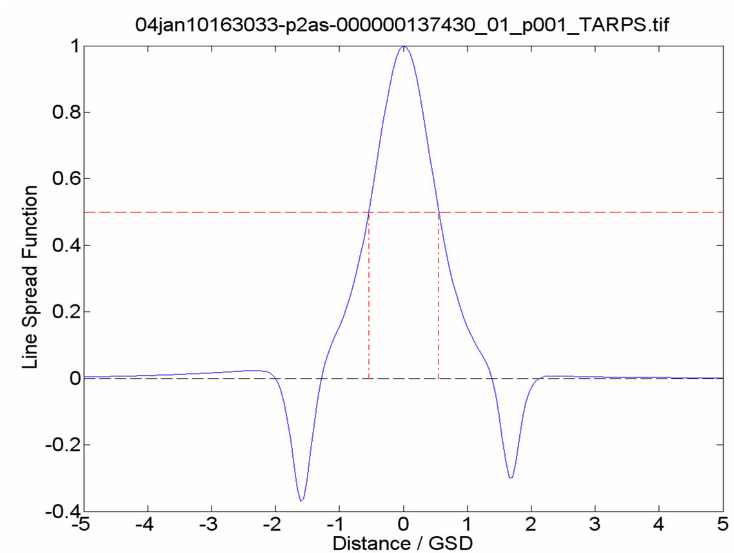
For the images processed with the MTF resampling kernel, the edge response has pronounced overshoots. Although the curve fitting is visibly less accurate in the MTF-kernel case, the analytical function approximates the image data near the edge response bend points quite well.



When the edge response analysis is repeated multiple times for the MTF images, this result is both reproducible and more frequent than the unique result in the CC case.

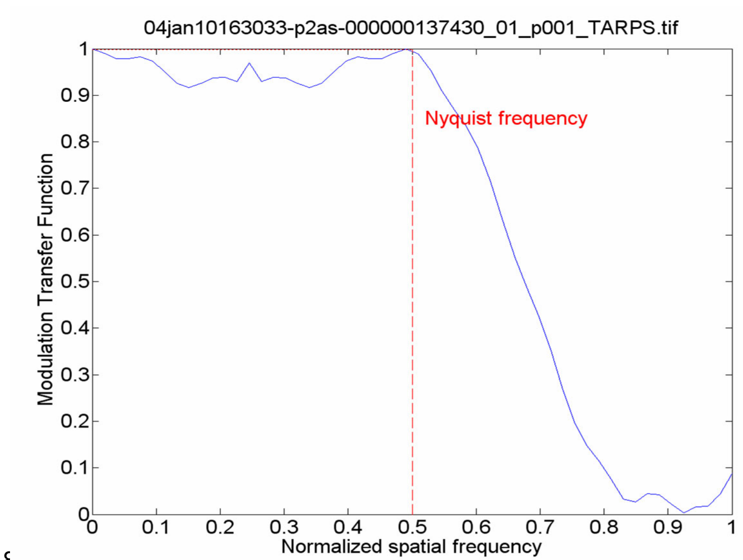
However, noise enhanced by the sharpening algorithm increases uncertainty of the results.

LSF and MTF for MTF Image



The LSF is narrower and has a different shape than in the unique CC case.

FWHM of LSF is approximately equal to 1.1 GSD.



The MTF seems to be flat and equal to one in the frequency range from zero up to the Nyquist frequency, with a fast decrease to near zero at higher frequencies.

This is definitely the desired effect of the MTF compensation methodology.

Simplified Edge Response for MTF Image

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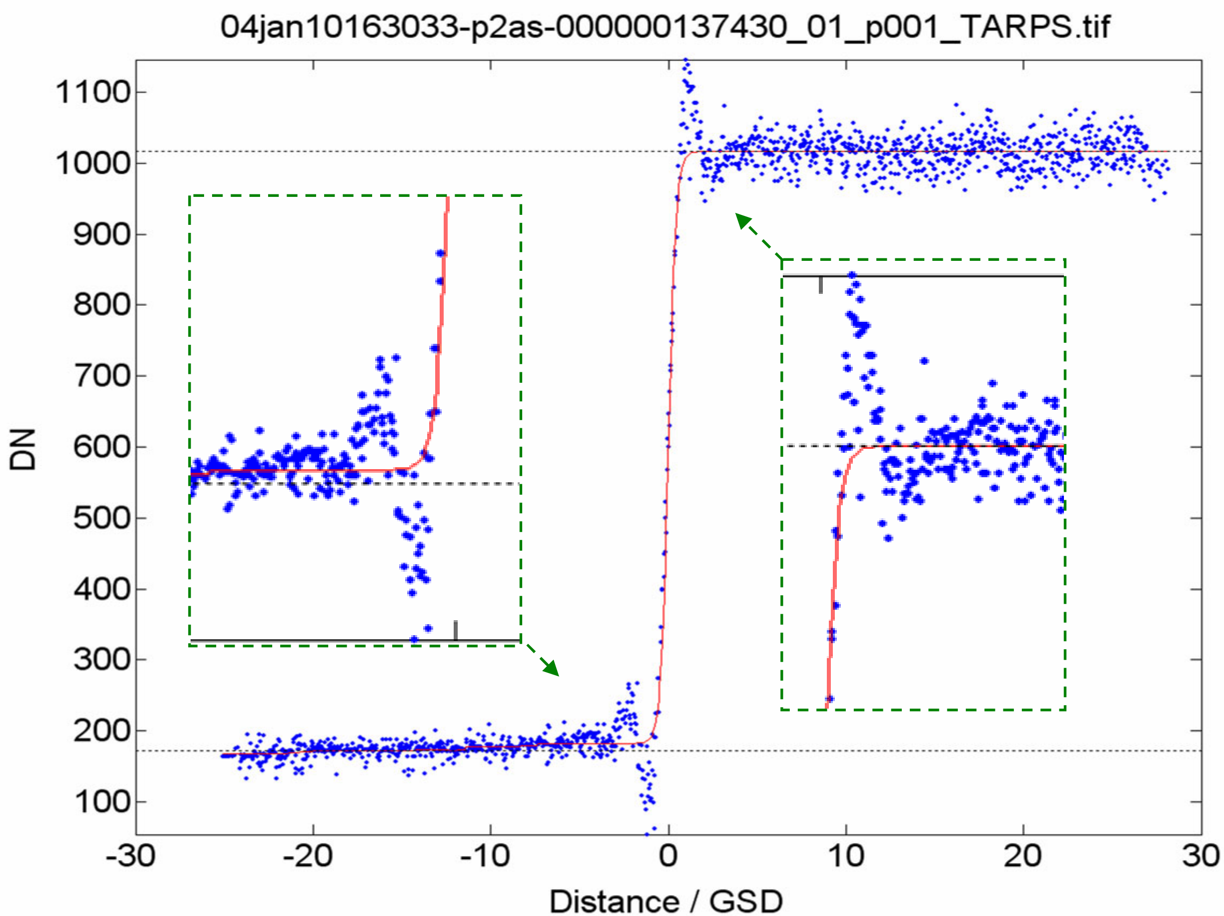
When the edge response analysis is repeated multiple times for the MTF images, in many cases the curve-fitting process is not as successful as shown on the preceding slides. The process often fails to detect the overshoots and produces an oversimplified approximation of the edge response.



Simplified LSF and MTF for MTF Image

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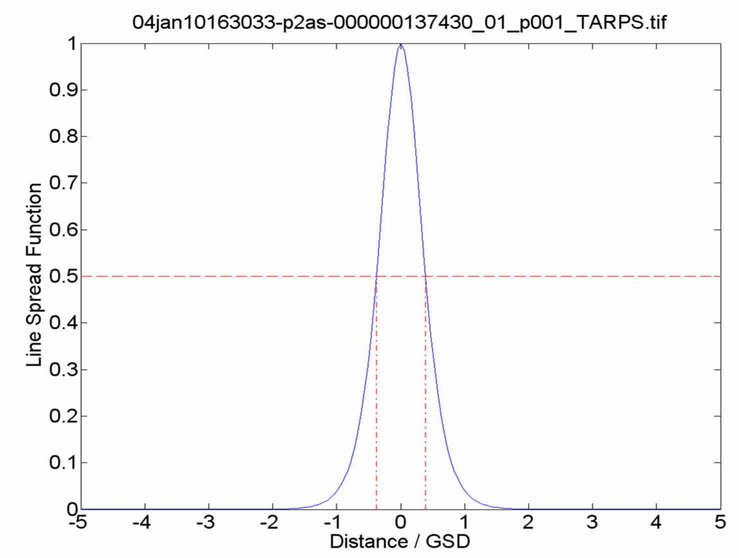
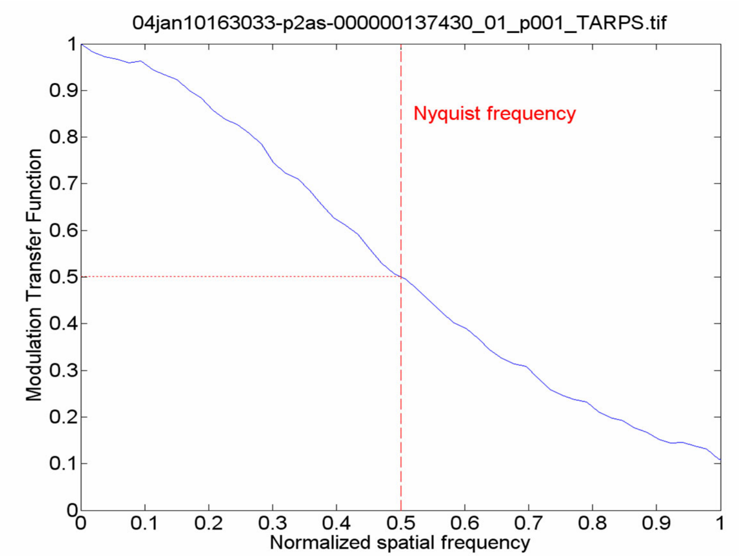


Shapes of both LSF and MTF determined from the simplified edge response resemble a Gaussian function and do not display any noticeable features.

FWHM of LSF is even smaller and approximately equal to 0.8 GSD.

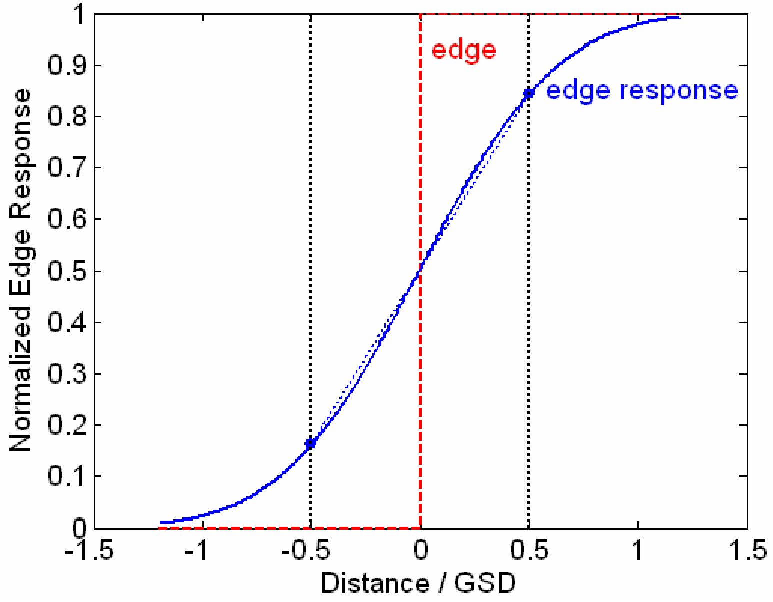


The value of MTF at the Nyquist frequency is approximately equal to 0.5.

Relative Edge Response

$$RER = \sqrt{[ER_X(0.5) - ER_X(-0.5)][ER_Y(0.5) - ER_Y(-0.5)]}$$

- Another measure of spatial resolution is a difference of normalized edge response values at points distanced from the edge by -0.5 and 0.5 GSD.
- This quantity is an estimate of an effective slope of the imaging system's edge response because distance between the points for which the difference is calculated equals the GSD.
- A geometric mean of the differences in two perpendicular directions is called Relative Edge Response (RER) and is one of the engineering parameters used in the *General Image Quality Equation* (GIQE) to provide predictions of imaging system performance expressed in terms of the *National Imagery Interpretability Rating Scale* (NIIRS).
- The NIIRS is a task-based scale that originated in the intelligence community, and it constitutes a benchmark used by imagery analysts, image acquisition managers, and sensor designers for rating applicability of image products for detecting, distinguishing, and identifying targets of interest.



The graph shows a normalized edge response as a function of distance from the edge. The dots indicate edge response points used in the calculations of the differences in the RER formula. These points are determined for each of the directions X and Y separately.

Meaning of RER in Remote Sensing

Radiance measured for each pixel is assumed to come from the Earth's surface area represented by that pixel. However, because of many factors, actual measurements integrate radiance L from the entire surface with a weighting function provided by a system's point spread function (PSF):

$$L_T = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} PSF(x,y)L(x,y)dxdy$$

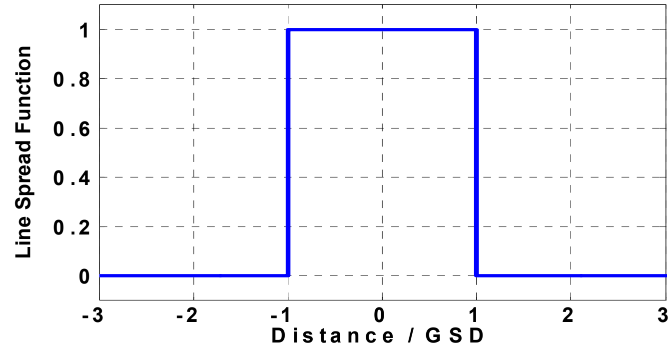
Part of radiance that originates in the pixel area is given by:

$$L_P = \int_{-0.5}^{0.5}\int_{-0.5}^{0.5} PSF(x,y)L(x,y)dxdy$$

One can show that the Relative Edge Response squared (RER^2) can be used to assess the percentage of the measured pixel radiance that actually originates from the Earth's surface area represented by the pixel:

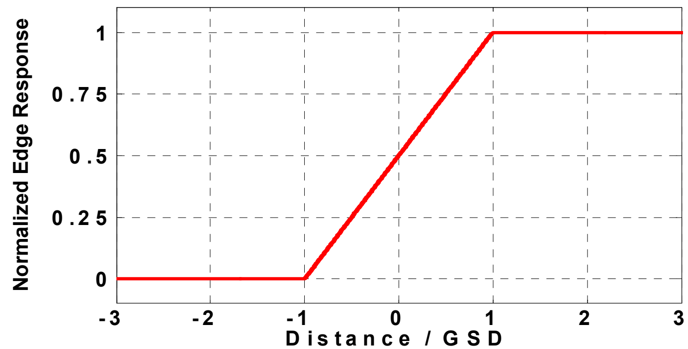
$$L_P / L_T \approx RER^2$$

A simple example:
Box PSF
Width = 2 GSD

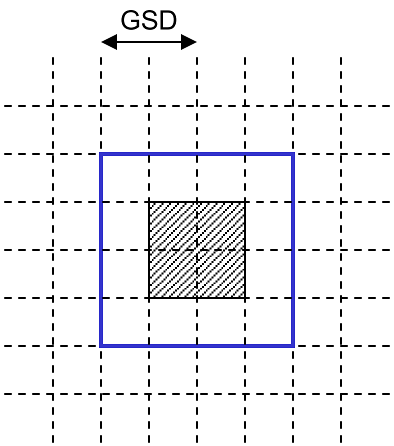


ER(0.5) - ER(-0.5) =
0.75 - 0.25 = 0.50

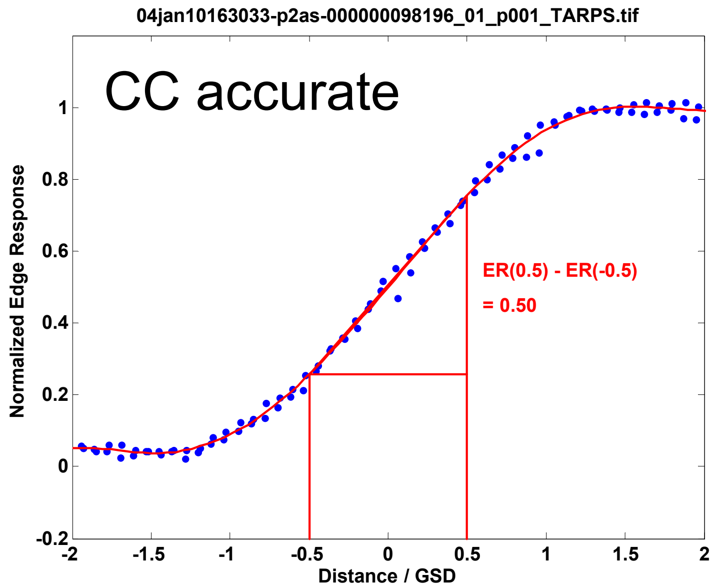
RER = 0.50

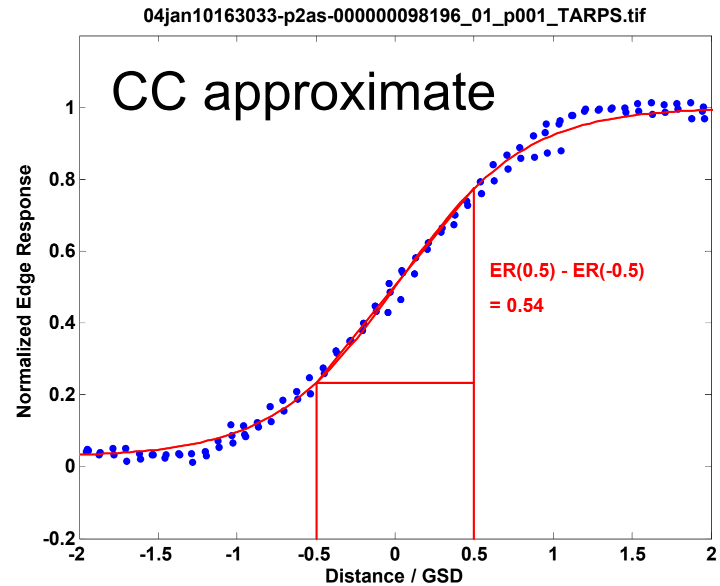


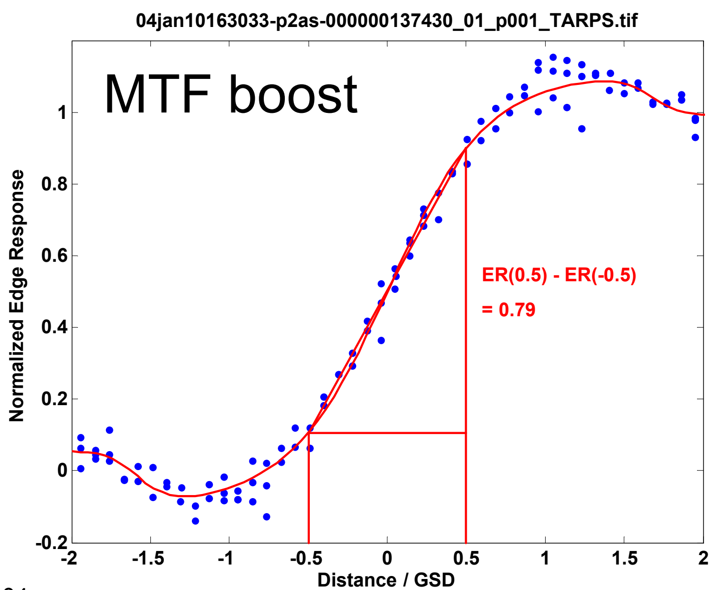
RER^2 = 0.25 means that 25% of information collected with the pixel PSF (blue square) comes from the actual pixel area (shadowed square)

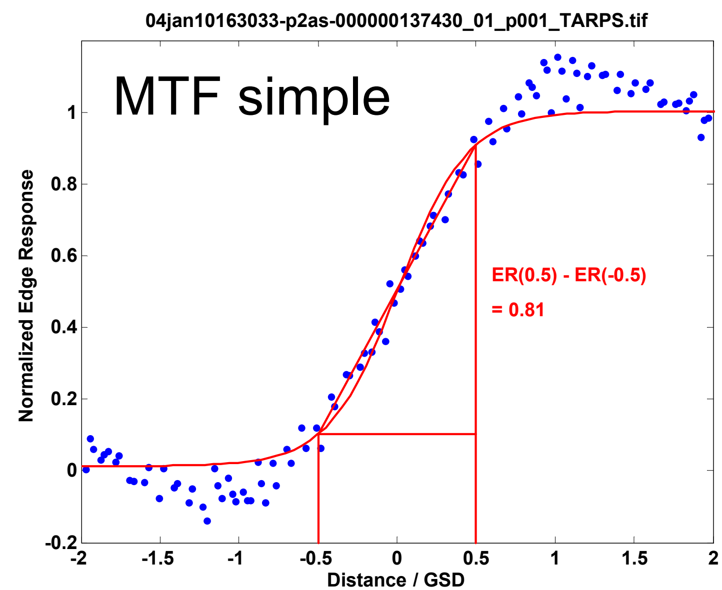


RER for CC and MTF Images









Summary of the Results

The table lists QuickBird panchromatic images used for spatial resolution characterization in 2003-2004 and results of the characterization shown as values of the MTF at the Nyquist spatial frequency and as the RER components (± uncertainty estimated from standard deviation of multiple results).

Image Tracking ID	Acquisition Site	Acquisition Date	Satellite Angle [°]		Resampled GSD [m]	Resampling Method	Target Direction	$MTF_{Nyquist}$	RER
			Zenith	Azimuth					
88502	Brookings, SD	2003-09-15	6.7	287.2	0.6	CC	Easting	0.14 ± 0.01	0.51 ± 0.01
98196	SSC, MS	2004-01-10	0.6	244.0	0.6	CC	Easting	0 / 0.14 ± 0.02	0.54 ± 0.01
102569	SSC, MS	2004-01-28	15.4	8.9	0.6	CC	Northing	0.11 ± 0.01	0.49 ± 0.01
76412	Brookings, SD	2003-09-15	6.7	287.2	0.6	MTF	Easting	0.55 ± 0.07	0.84 ± 0.01
137430	SSC, MS	2004-01-10	0.6	244.0	0.6	MTF	Easting	1 / 0.50 ± 0.01	0.81 ± 0.01
102569	SSC, MS	2004-01-28	15.4	8.9	0.6	MTF	Northing	0.41 ± 0.04	0.76 ± 0.01

These results show that RER is much less sensitive to accuracy of the curve fitting than the value of MTF at Nyquist frequency. Therefore, the RER/edge response slope is a more robust estimator of the digital image spatial resolution than the MTF. For the QuickBird panchromatic images, the RER is consistently equal to 0.5 for images processed with the CC resampling and to 0.8 for the MTF resampling.