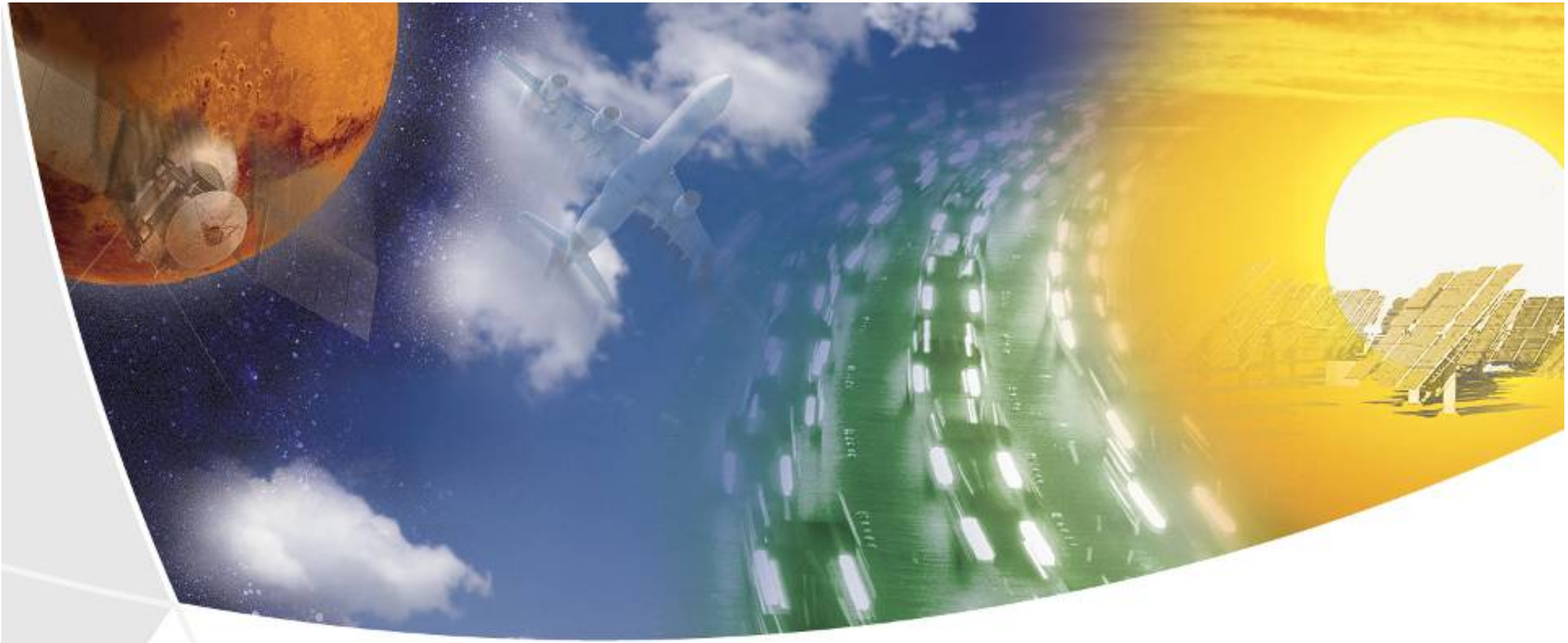

Spatial Resolution Assessment from Real Image Data

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in der Helmholtz-Gemeinschaft

Institute for Robotics and Mechatronics
Optical Information Systems

Optical Information Systems

- **HiRes**: High resolution In-Orbit-Instruments (GSD < 1m)
- **HiSpec**: hyperspectral systems, λ = 400 nm – 14 µm (VIS…IR)
- **HiProc**: real time processing, from data to information

Space Systems

- **SmartSat**: innovative, low-cost small satellites
- **CMMI**: Software-Engineering, Capability Maturity Model

Current Projects

MERTIS

- IR-Spectrometer on BepiColombo-Mission λ≈(7…14μm)
- ESA-Project

KompSat3

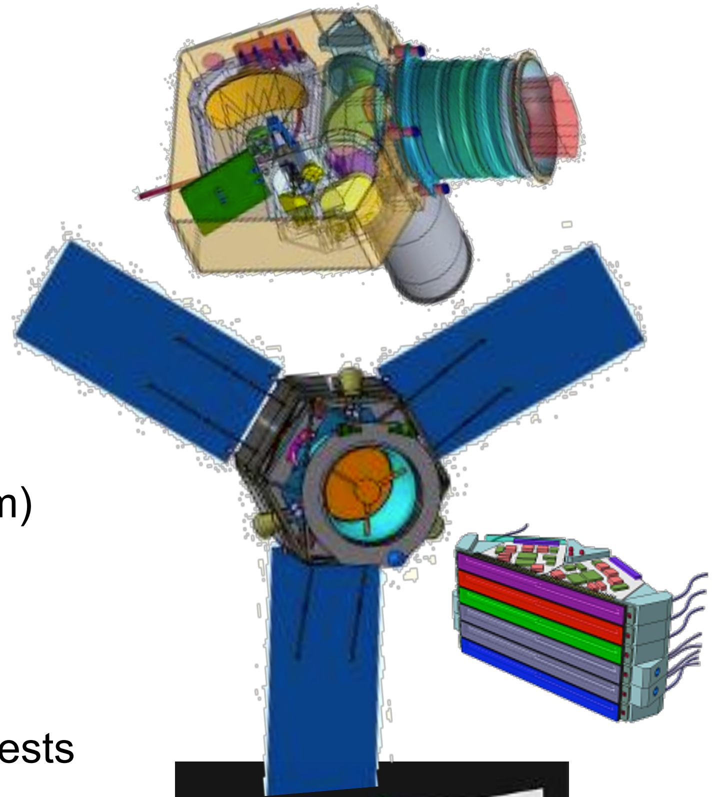
- Geometrically high resolution Sensor (0.7m)
- Project of the Korean Space Agency, Cooperation with EADS

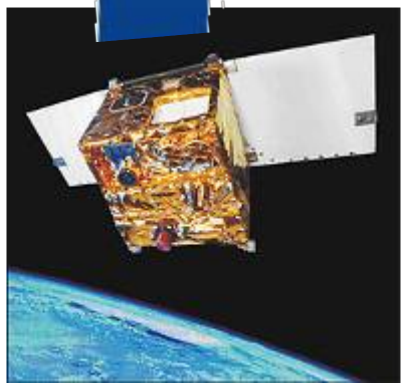
TET/OOV

- Small Satellite as platform for technology tests
- Project of the German Space Agency

3D-Worlds

- Virtual World generated from stereo images
- Different Customers





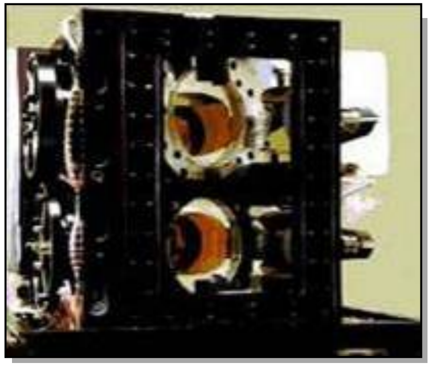
Heritage: Spaceborne Sensors

Michelson Interferometer
Venus Mission 15 **PMV**

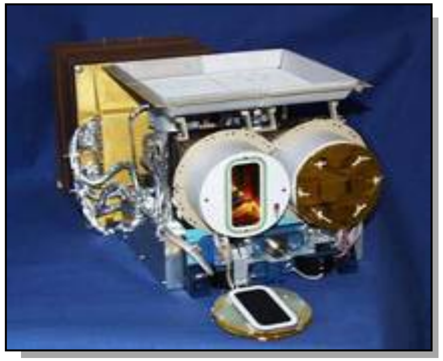
Star Navigation
ASTRO - 1 (M)

CCD-Line Camera
Mars 96 **WAOSS**

19 Channel Imager
MOS-IRS

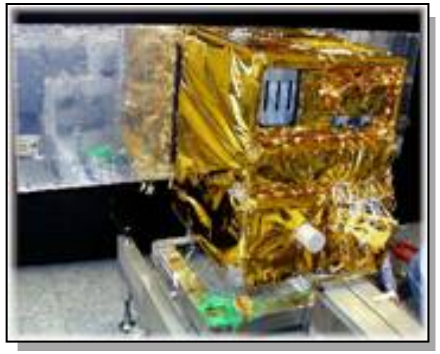


Michelson Interferometer
Mars EX **PFS** (running)



MIR and TIR Line Scanner
HSRS (running)

Hyperspectral Imager **VIRTIS**
Comet Churyumov-Gerasimenko (running)

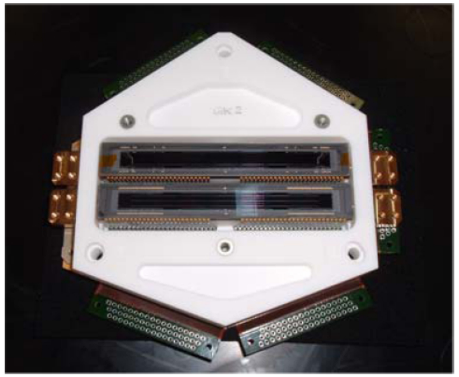


Bi-spectral IR Detection
BIRD (running)

Camera technology in Space

Rapid Eye

- Constallation with 5 Satellites for agriculture mapping and cartography
- 6.5m GSD, 77km swath
- 5 spectral bands (blue, green, red, red edge, near infrared)
- Focal plane provided by DLR based on ADS40 heritage



Agenda

- Introduction / motivation
- Image quality
- PSF – Determination from real image data
- Results / outlook

Introduction / Motivation

- Instrument in-orbit behaviour / traceability
- Models, algorithms & measurements for all components of the camera & pre-processing
  - PSF / MTF
  - SNR
  - Pre-processing, image restoration
  - Geometric accuracy / direct geo-referencing
  - Radiometric accuracy (including atmospheric correction)
  - …

- Parameter-determination from Lab-calibration
- Test and verification with data from real images

Sampling, Resolution, Image Quality – Object Interpretability

- (Spatial) resolution - ability to resolve (spatial) detail or detect (spatial) objects or feature of certain size
- Resolution is determined by a number of factors, including GSD, the performance of the camera optics, pixel size and the sensor noise
- Additional image processing algorithms also influence the resolution
- Image quality – smear & noise

- The concept of object interpretability provides a direct link to the design and application of optoelectronic sensors
- Same standards are the US “National Image Interpretability Rating Scales” (http://www.fas.org/irp/imint/niirs.htm) and NATO STANAG 3769, which recommends the appropriate ground pixel size for the detection, recognition, identification in some cases also technical analysis of image objects.

NIIRS

- Jon C. Leachtenauer: Image Quality Equations and NIIRS
- NIIRS is an empirically, criteria-based, 10-point scale used to indicate the amount of information that can be extracted by imagery. A commonly accepted form of the GIQE that accounts for the effects is:

$$NIIRS = c_0 + c_1 \cdot \log_{10} GSD + c_2 \cdot \log_{10} RER + c_3 \cdot \frac{G}{SNR} + c_4 \cdot H$$

- GIQE 4.0 (for RER<0.9)

c_0 = 10.251, c_1 = -3.16, c_2 = 2.817, c_3 = -0.334, c_4 = -0656

- GSD - system ground sample distance,
- RER - system post-processing relative edge response,
- G - system post-processing noise gain,
- SNR - signal-to noise ratio of the unprocessed imagery,
- H - system post-processing edge overshoot factor.

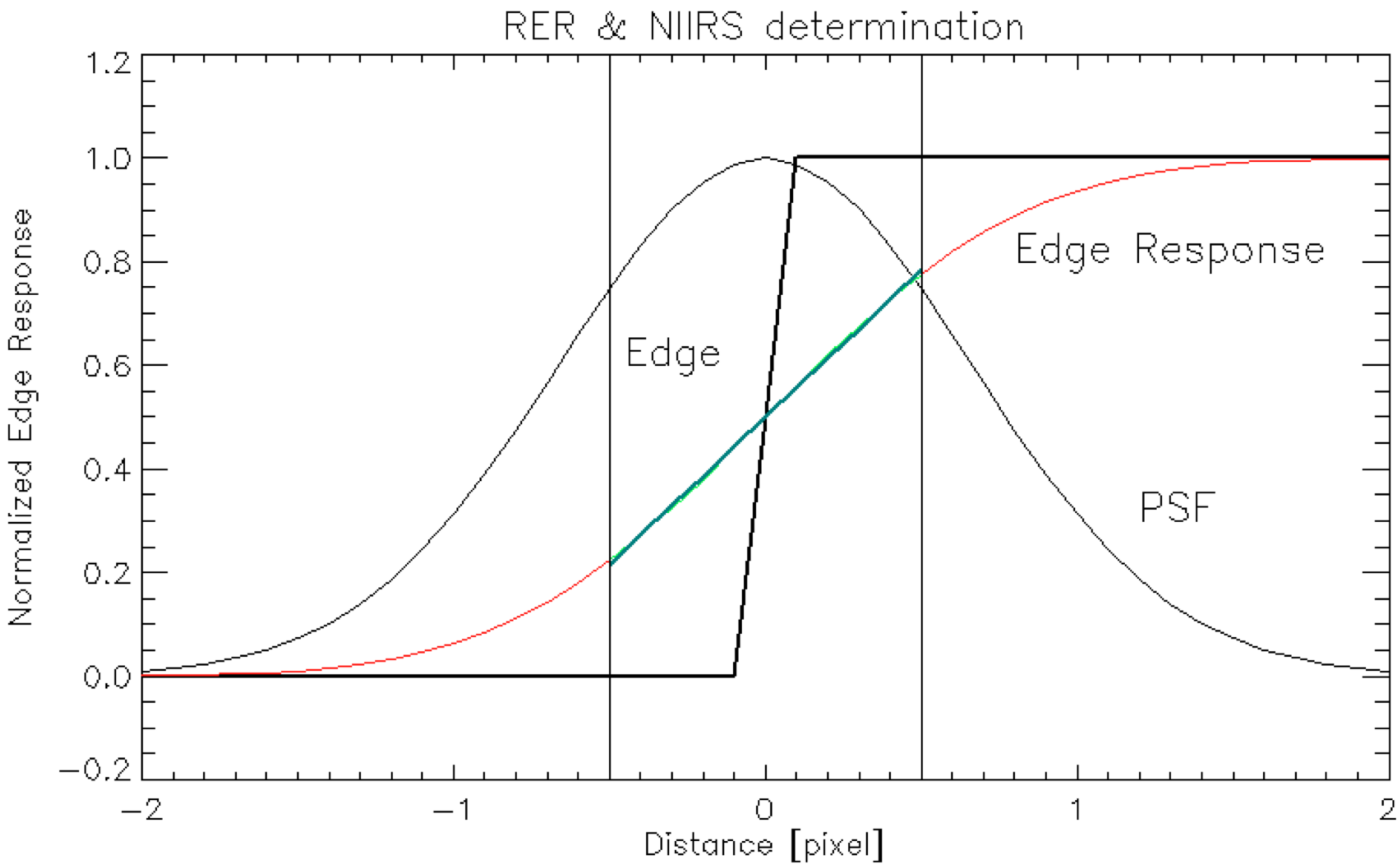
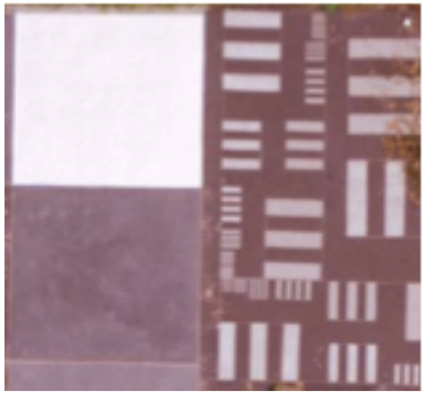

RER & NIIRS determination
Normalized Edge Response
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−2
−1
0
1
2
Distance [pixel]
Edge
Edge Response
PSF

Image Quality Determination
Calibration / Verification

- Image quality investigation in all mission phases
- Influence of pre-processing algorithms (Brunn, JACIE-Conf.)
- Focus / defocus assessment of the satellite camera

- Radiometric and geometric accuracy based on artificial test fields
  - Homogeneous targets of different size
  - Well measured reflectance and location
  - Reference measurement on Earth
  - Several campaigns on different test sites



PSF – Determination from real Image Data

- PSF - response of an imaging system to a point-like object
- Based on the definition of a translation invariant PSF

$$V(x,y) = \iint dx'dy' H(x-x', y-y') \cdot U(x', y')$$

- with knowledge of the two-dimensional input signal U(x', y') and measurement of V(x, y) the PSF of the system H(x, y) can be derived
- Particularly simple and transparent solutions are obtained for point (PSF), linear (LSF) and edge signals (ESF)

PSF, LSF & ESF

We can measure

- PSF from response of a point-like object (delta-function)

$$U(x',y') = \delta(x',y') \Rightarrow V(x,y) = H(x,y)$$

- LSF from response of a line-like object (parallel to y-axis)

$$U(x',y') = \delta(x') \Rightarrow V(x) = \int_{-\infty}^{\infty} dx' H(x-x')$$

- ESF from response of a black to white edge (parallel to y-axis)

$$U(x',y') = \begin{cases} 0 & x > 0 \\ 1 & x \leq 0 \end{cases} \Rightarrow V(x) = \int_{-\infty}^{x} dx' H(x-x')$$

- LAB: PSF / LSF / ESF with pinhole, slit or (slanted) edge
- From real images: ESF from light to dark transitions

ISO 12233

- ISO 12233: Photography — Electronic still-picture cameras — Resolution measurements
- Describes the spatial frequency response (SFR) measurement method
- Digitized image values near slanted vertical and horizontal black to white edges are digitized and used to compute the SFR values
- The use of a slanted edge allows the edge gradient to be measured at many phases relative to the image sensor detector-elements, in order to eliminate the effects of aliasing

Evaluation Procedure

- Selection of an area with a strong contrast transition
- Usual, the signal is differentiated to determine directly the LSF (see ISO 12233)
- The problem is that the noise increases dramatically during differentiation
- Instead of the PSF the edge spread function (ESF) was determined directly
- It is assumed that the PSF is described by a normal distribution:

$$H(x) = \frac{1}{\sigma_H \sqrt{2\pi}} \cdot e^{-\frac{x^2}{2 \cdot \sigma_H^2}}$$

- The size of σ_H gives a quantitative value for the assessment of the PSF
- The determination of this value suffices for the description of the PSF and the change by the application of the different filters

MTF - Resolution

- Frequency response (OTF – optical transfer function):

$$\tilde{H}(K_x, K_y) = \left|\tilde{H}(K_x, K_y)\right| e^{-j\phi_H(K_x, K_y)}$$

MTF (modulation transfer function)

- Resolution depends on:
  - Optics (camera misfocus)
  - Detector
  - Motion blur
  - Atmosphere
  - ...

$$MTF = \left|\tilde{H}(K)\right| \cong e^{-2\pi^2 \cdot \sigma_{MTF}^2 K^2}$$

$$\left|\tilde{H}(K)\right| = \left|\tilde{H}_O(K)\right| \cdot \left|\tilde{H}_D(K)\right| \cdot \left|\tilde{H}_M(K)\right|$$

$$\sigma_{MTF}^2 = \sigma_O^2 + \sigma_D^2 + \sigma_M^2$$

MTF – Resolution (rough calculation)

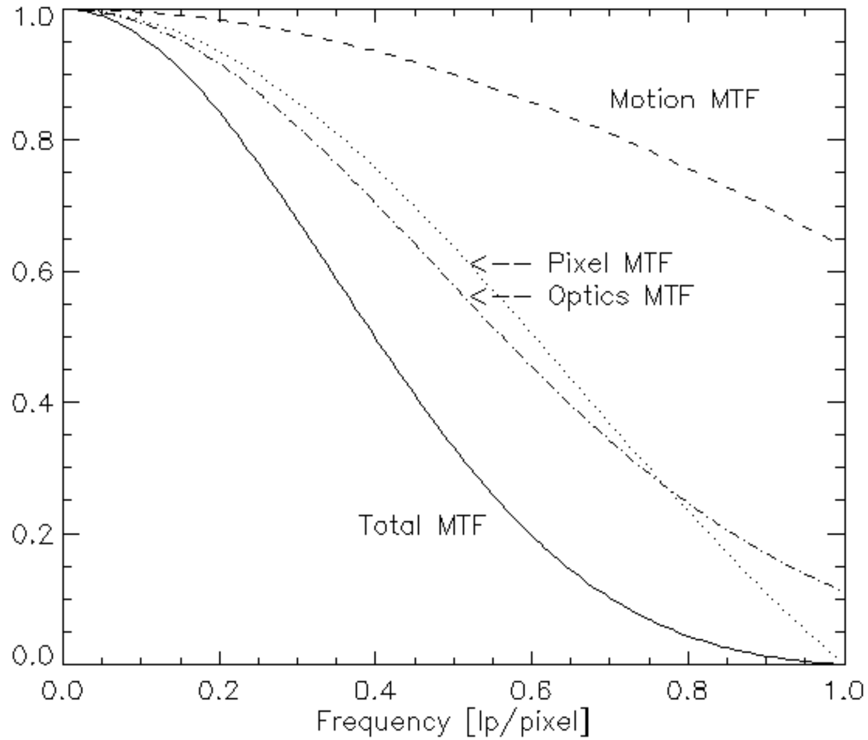
- Frequency response (OTF – optical transfer function):

$$\tilde{H}(K_x, K_y) = \left|\tilde{H}(K_x, K_y)\right| e^{-j\phi_H(K_x, K_y)}$$

- Sensor components:
  - Optics (camera misfocus)
  - Detector
  - Motion blur

$$\sigma_D = \sigma_D^0 \quad \sigma_O \approx \sigma_D^0 \quad \sigma_M \approx \sigma_D^0 / 2$$

$$\sigma_{MTF} = \sqrt{\sigma_O^2 + \sigma_D^2 + \sigma_M^2} \approx 0.75 \cdot \delta_{pix}$$



MTF – Resolution (rough calculation)

- Derivation of performance measures
- MTF @Nyquist - frequency corresponds here to n = ½ [1/pixel]:

$$\tilde{H}\left(\nu\right) = e^{-2\cdot\pi^2\cdot\sigma_H^2\cdot\nu^2} \quad \leftrightarrow \quad \tilde{H}\left(\nu = \frac{1}{2}\right) = e^{-\frac{\pi^2\cdot\sigma_H^2}{2}}$$

- An important parameter for the description of the distribution is Full-Width Half-Maximum, or FWHM (for a normalized distribution):

$$\frac{1}{2} = e^{-\frac{x^2}{2\cdot\sigma_H^2}} \rightarrow \quad x_{+FWHM} = \sigma_H \cdot \sqrt{2\cdot\ln\left(2\right)}$$

$$\Delta_{FWHM} = x_{+FWHM} - x_{-FWHM} = 2\sigma_H \cdot \sqrt{2\cdot\ln\left(2\right)}$$

Evaluation Procedure

$$U(x',y') = \begin{cases} a & x > x_0 \\ b & x \le x_0 \end{cases} \Rightarrow V(x) = \int_{-\infty}^{x} dx' H(x - x')$$

- By breaking the integral, interchanging the limits of integration and using the probability (error) integral

$$\Phi\left(\frac{x - x_0}{\sigma_H \sqrt{2}}\right) = \frac{1}{\sigma_H \sqrt{2\pi}} \int dx' e^{-\frac{(x-x')^2}{2\sigma_H^2}}$$

- One can obtain for the signal

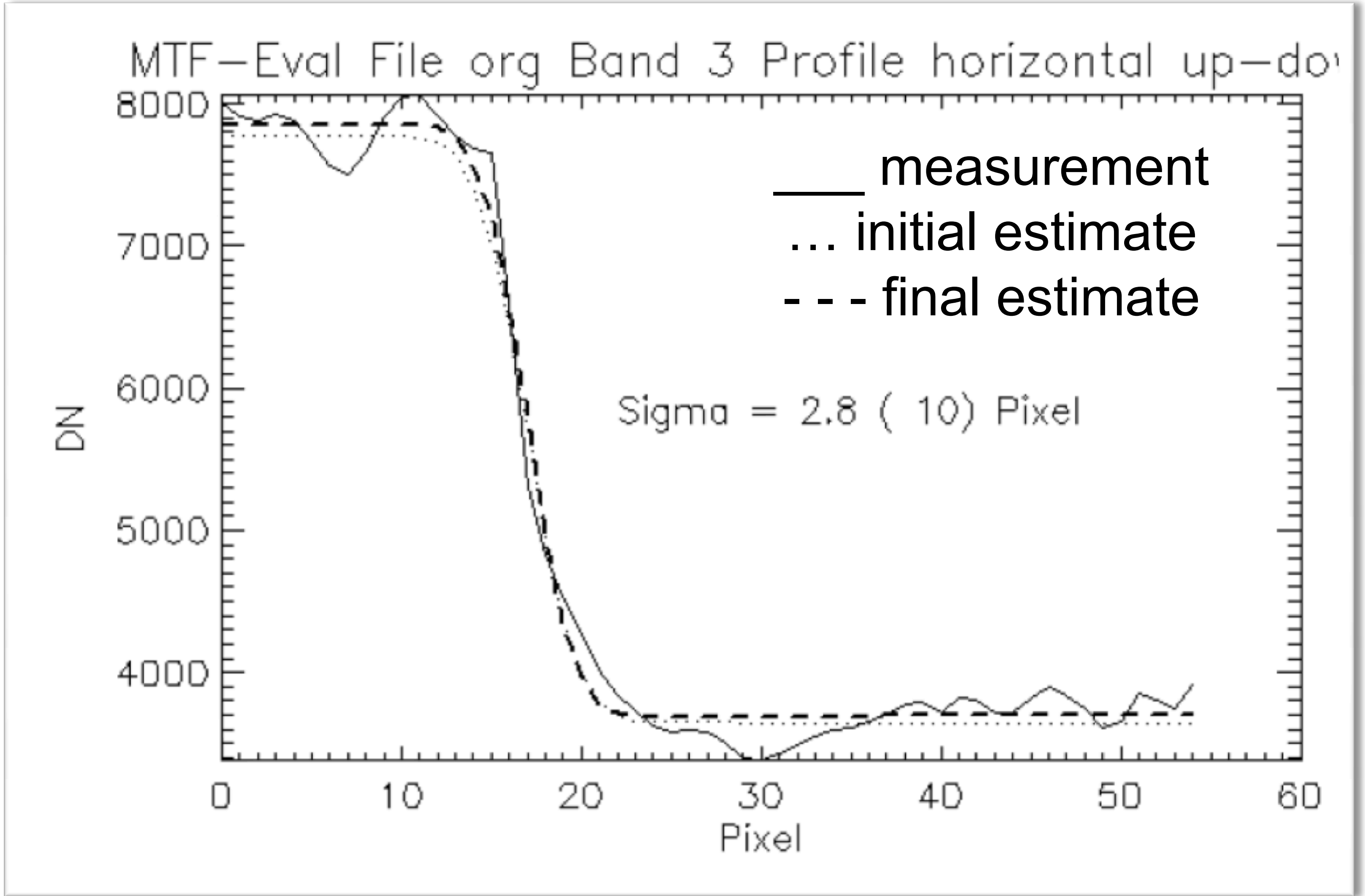
$$V(x) = a_0 \cdot \Phi\left(\frac{x - a_1}{a_2 \sqrt{2}}\right) + a_3 + a_4 \cdot x$$

- The value a_2 is according to the σ_H and $a_1 = x_0$
- An offset and a linear change of the image gray values in addition are estimated within this approach

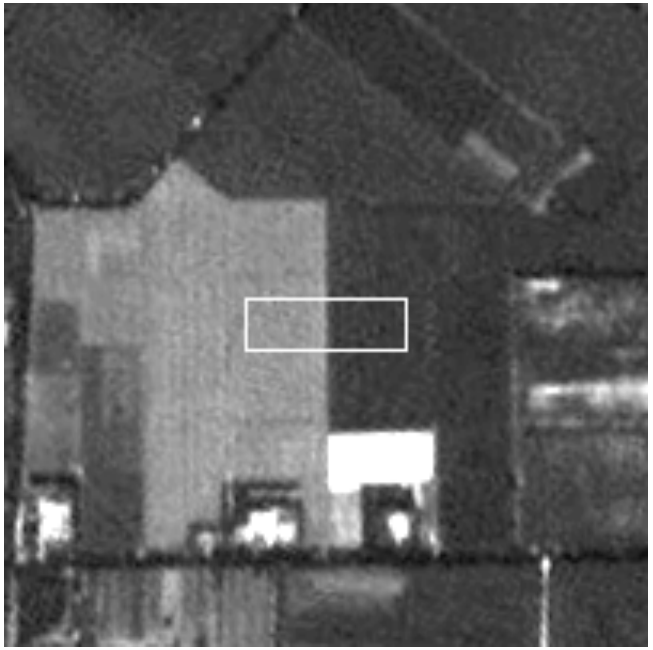
Evaluation Procedure

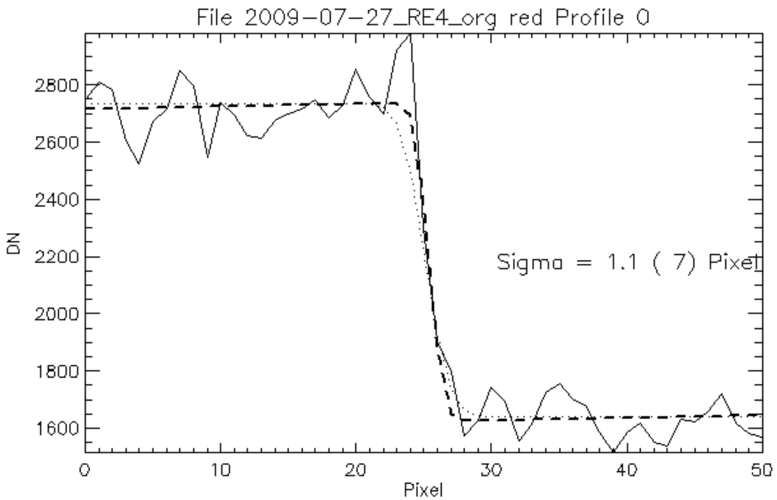
- The determination of the parameters was carried out in the context of a nonlinear least squares fit (Bevington and Robinson, 2002)
- This method is a gradient-expansion algorithm which combines the gradient search with the method of linearizing the fitting function
- The value a_2 is according to the σ_H.
- The measurement unit of σ_H is arbitrary. Here σ_H is measured in pixel.
- $a_0=(a-b)/2$, $a_3=(a+b)/2$ (from profile data left & right from the edge)
- An offset and a linear change of the image gray values in addition are estimated within this approach
- Initial values for
  - $a_2= \sigma_H = 1$
  - a_1 from edge position

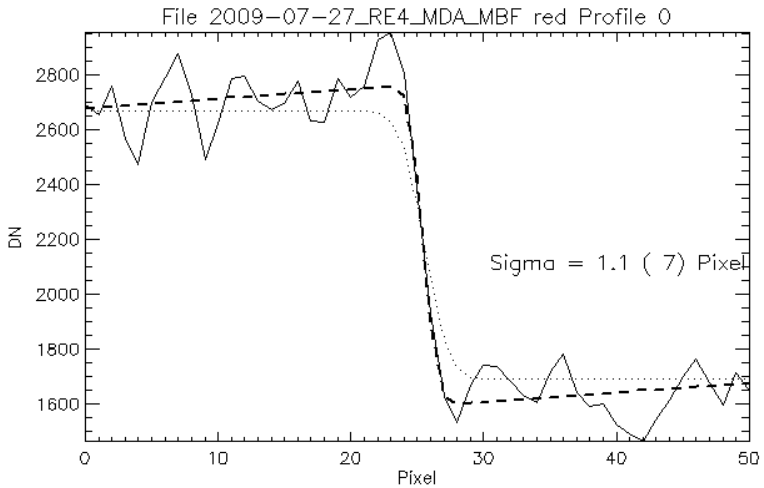
Evaluation Procedure



Results

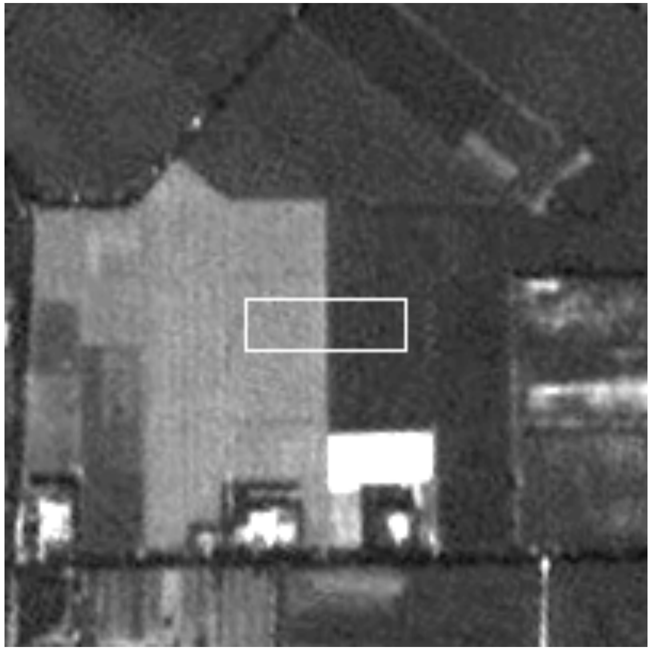



File 2009-07-27_RE4_org red Profile 0
Sigma = 1.1 (7) Pixel
DN
Pixel
2800
2600
2400
2200
2000
1800
1600
0
10
20
30
40
50


File 2009-07-27_RE4_MDA_MBF red Profile 0
Sigma = 1.1 (7) Pixel
DN
Pixel
2800
2600
2400
2200
2000
1800
1600
0
10
20
30
40
50

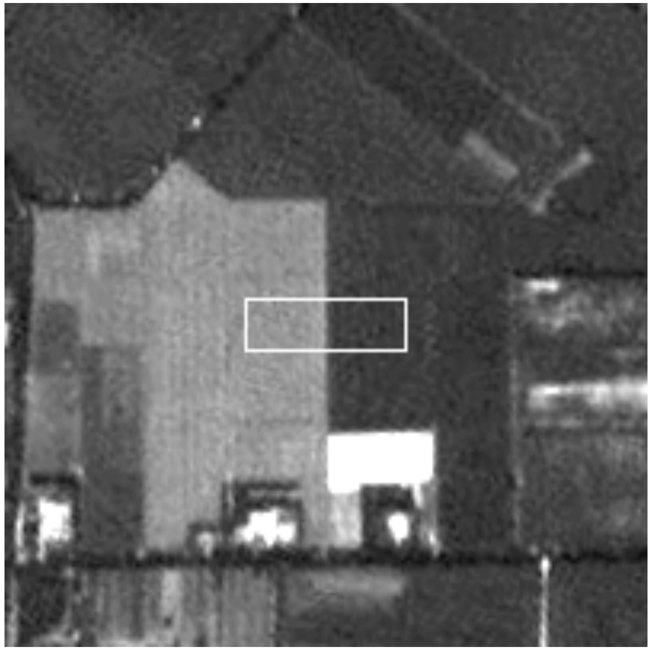
Further Improvements

- Evaluate more than one profile
- Accuracy estimation



File Name	Easting	Northing	Channel	σ_{MTF}	Standard-deviation
2009-07-27_RE4_org	442330	5887445	NIR	1.07	0.12
2009-07-27_RE1_org	399080	5875830	green	1.74	0.41

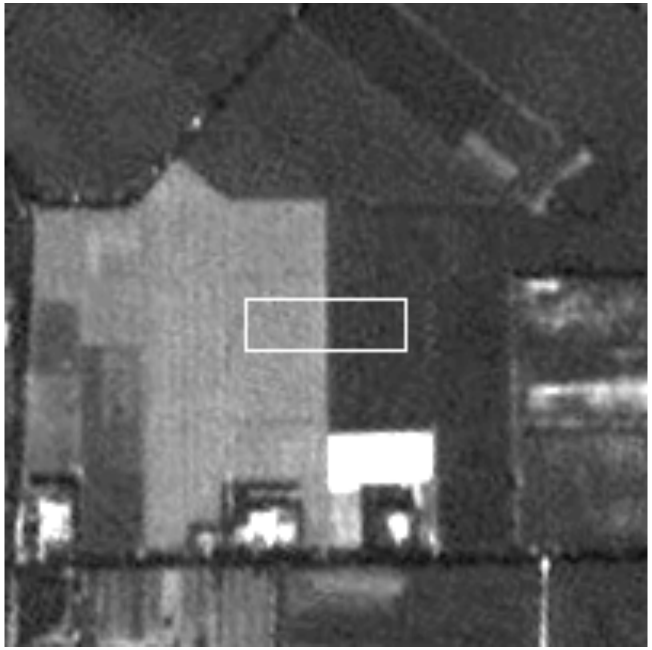
Further Improvements



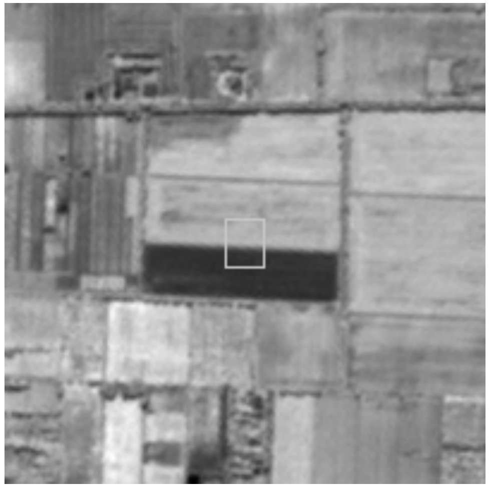
- Evaluate more than one profile
- Accuracy estimation
- Some uncertainties in the results
- The quality of the result depends strongly on signal-noise and the PSF itself
- Only few values particularly at the transition from bright to dark are available for the evaluation (“under-sampling” problem)
- Different approaches were suggested to solve this problem (Helder, et. all, 2004, ISO – slanted edge method)

Further Improvements

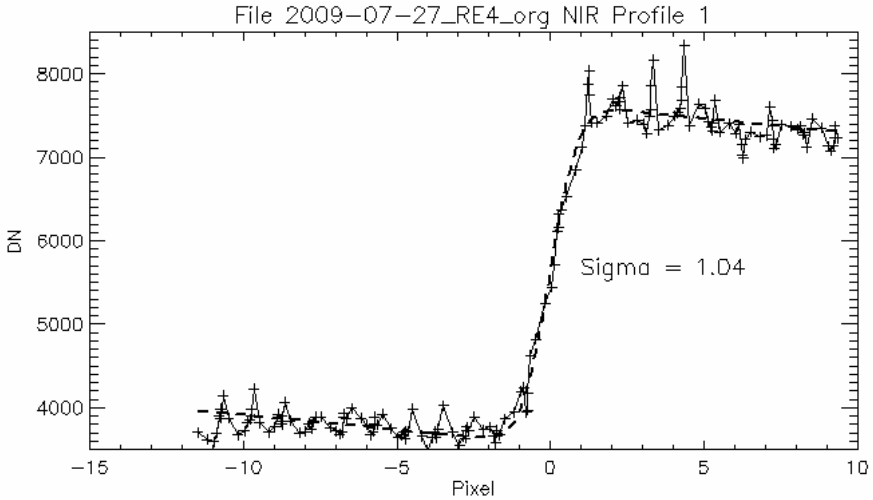
- Evaluate more than one profile
- Accuracy estimation

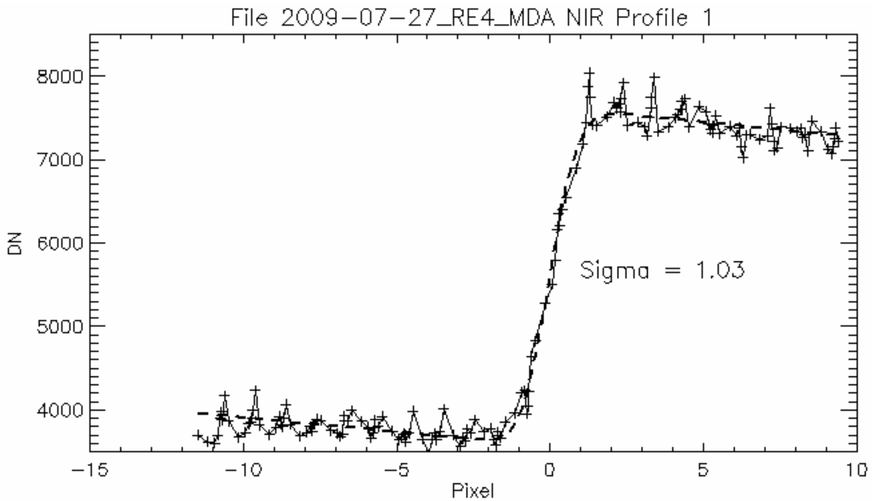


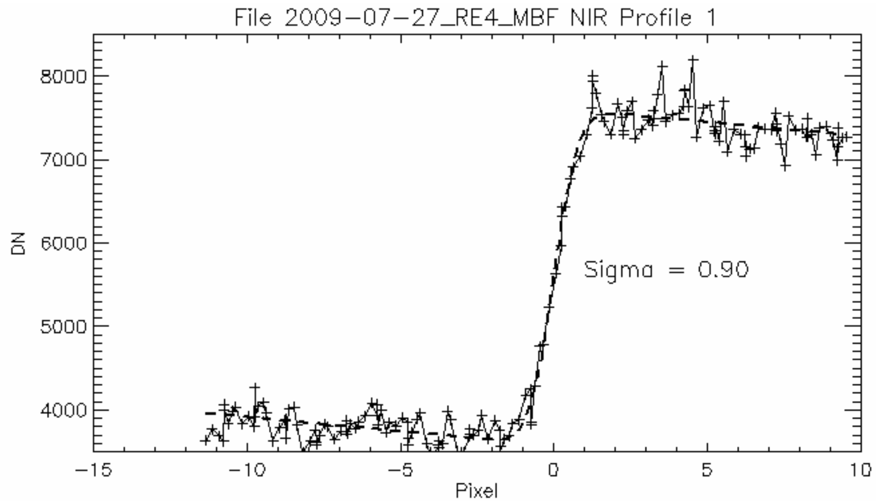
- On a slanted edge the shift of the measured profiles is determined by the parameter a_1
- One then takes into account this shift and puts all profiles together in the right order in one profile
- Through this one gets considerably more points in the transition region

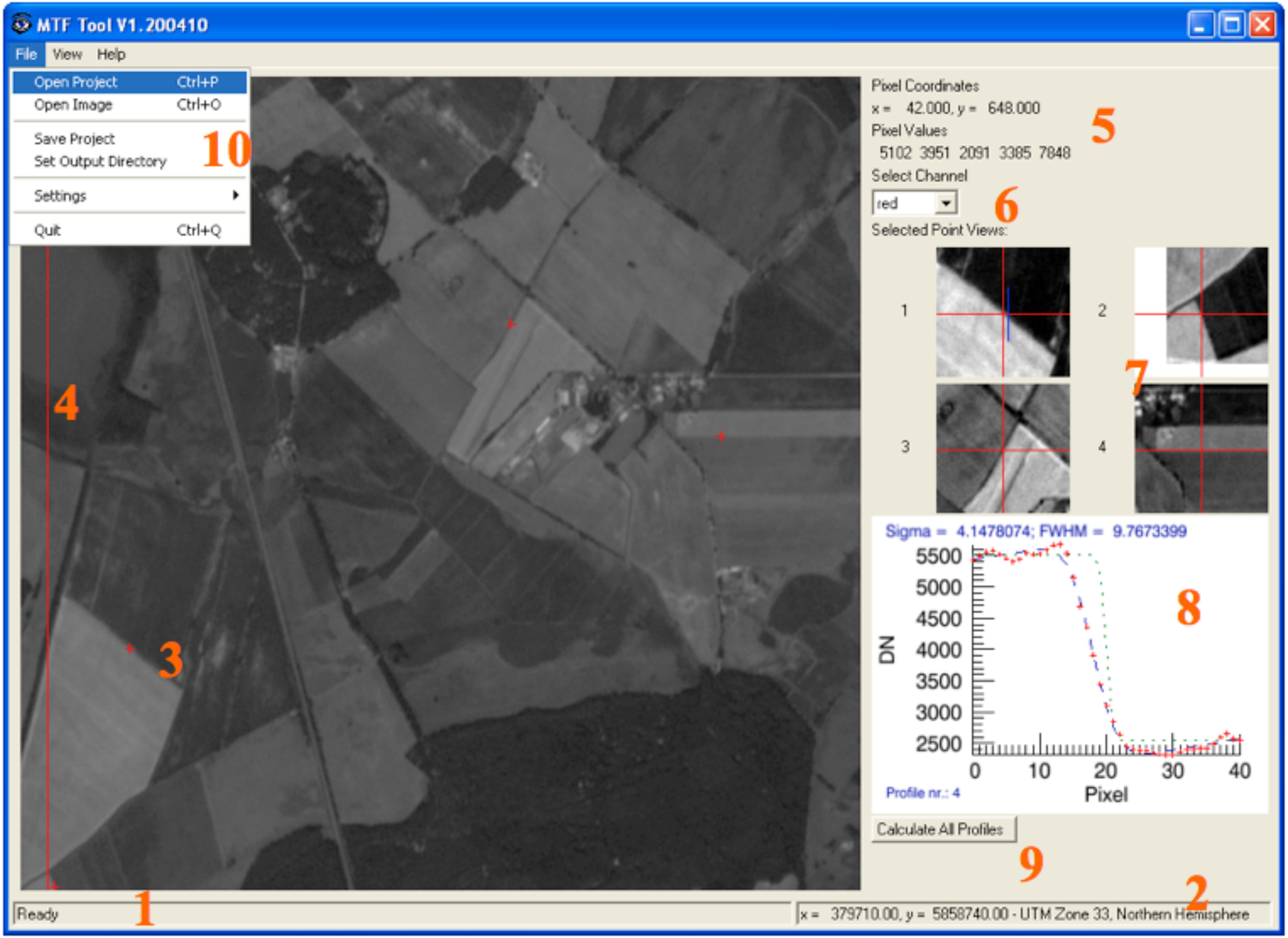


2009-07-27_RE1_org








MTF Tool V1.200410
File
View
Help
Open Project Ctrl+P
Open Image Ctrl+O
Save Project
Set Output Directory
Settings
Quit Ctrl+Q
Pixel Coordinates
x = 42.000, y = 648.000
Pixel Values
5102 3951 2091 3385 7848
Select Channel
red
Selected Point Views:
1
2
3
4
Sigma = 4.1478074; FWHM = 9.7673399
DN
Pixel
Profile nr.: 4
Calculate All Profiles
Ready
x = 379710.00, y = 5858740.00 - UTM Zone 33, Northern Hemisphere
1
2
3
4
5
6
7
8
9
10

MTF tool main window

- Status bar (1) displays important notifications
- UTM bar (2) gives UTM coordinates of the actual mouse cursor position if proper GeoTiff information is loaded
- An image point for profile measurements is marked with a red cross (3)
- Border line (4) limits the area where points can be measured. The size depends on the particular profile dimension.
- In the top right corner (5) the position of the cursor is displayed. Additionally, all channel values are given.
- A channel for profile measurements is chosen by the '*select channel*'-drop down list (6)
- Up to four views (7) of the measured image points are shown right from the main window
- In the lower right corner the particular profile view is displayed (8)
- Finally, the file menu (10) offers some basic operations.

Results / Outlock

- We presented a robust method and implementation for PSF determination based on a Gaussian shaped PSF
- With the help of the described procedure a more exact determination of the PSF can be carried out
- Particularly the differences at the application of the filters can be examined
- Error sources:
  - Model limitations
  - The considered edge is in reality not an exact transition. This is possible only with a test field.
  - Atmospheric blurring, platform jitter, etc.
- Automatic approaches for NIIRS determination
- Investigation of alternative image quality criteria, based on physical sensor models

References

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- Helder, D., T. Choi and M. Rangaswamy (2004). “In-flight characterization of spatial quality using point spread function”. In: Morain, S. A. and A.M. Budge (2004). "Post-Launch Calibration of Satellite Sensors", Taylor & Francis Group, London UK
- Bevington, P.R. and K.D. Robinson (2002). “Data Reduction and Error Analysis for the Physical Sciences”, Mcgraw-Hill Higher Education
- ISO 12233:2000 Photography -- Electronic still-picture cameras -- Resolution measurements, 2000