Atmospheric correction for airborne hyperspectral data - the ATCOR approach -

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1. Brief recap - basics of remote sensing, the image chain

2. Atmospheric correction
   - Atmospheric window regions
   - Absorption and scattering
   - Visibility (meteorological range)
   - Radiation components (path, surface reflected, adjacency)
   - Radiation components in mountainous terrain
   - Radiative transfer codes

3. The ATCOR approach – reflective region
   - Aerosol retrieval (optical thickness, visibility)
   - Water vapor retrieval
   - Haze removal
   - Cirrus removal
   - De-shadowing

4. EnMAP uncertainty estimation example
The image chain approach (Schott 2007) describes

The way of a photon
from the emitting source
through the atmosphere
to the Earth’s surface
back to the atmosphere
to the sensor
1st: Radiation Source
Every object is emitting electro-magnetic radiation
Every object is emitting **electro-magnetic radiation according to its temperature.**

**Sun:**
- \(~5800 \text{ K blackbody,} \)
- radius \( \approx 0.7 \times 10^6 \text{ km} \)
- Subtended angle = \(0.56^\circ\)

**Earth:**
- \(~300k \text{ average surface temp.} \)
- \(\text{Lmax at } 10 \mu\text{m (}=10.000\text{nm)}\)
Electromagnetic wave (Maxwells Equation)
Electric perpendicular to magnetic
\[ c = \lambda \times v \]
\( c \)…Lightspeed in vacuum \( 3 \times 10^8 \text{ m s}^{-1} \)
\( v \)…Frequency

Energy
\[ q = h \times v \]
h: Planck’s Constant: \( 6.63 \times 10^{-34} \text{ [J s]} \)
\( \Rightarrow \) Higher energy per photon with shorter wavelength

Energy per Photon:
green 0.55 \( \mu \text{m} \): \( 3.61 \times 10^{-19} \text{ J} \)
TIR 12 \( \mu \text{m} \): \( 1.66 \times 10^{-20} \text{ J} \)
\( \Rightarrow \) 22times higher energy!
2nd: Atmosphere
Solar Irradiance [kW m\(^{-2}\)]

ideal blackbody at 5800 K
extraterrestrial (outside atmosphere)
at sea level
Basics – Atmosphere

Ultra-Violet „Visible“

Near Infrared

Mid-IR

Thermale Infrared „heat“

0.4 µm

0.7 µm

Short-Wave IR

NIR

MIR

UV

VIS

NIR

I

II

TIR

FIR

Transmission [%]

Wavelength [µm]

0

100
3rd: Interaction with Matter
- Absorption (uptake of energy)
  - Electron transfer, rotation, vibration
    - Heating, change in matter, emission

- Emission („release“ of energy)
  - Electron transfer, rotation, vibration

- Reflection
  - Change of direction without energy uptake

- Transmission
  - Transfer without absorption or reflection

**Synopsis**

- **Basics – Interaction with matter**
  - Photosynthesis
  - Interaction with matter
Energy balance relationship:

- \( E_{\text{emitted by sun}} = E_{\text{reflected}} + E_{\text{transmitted}} + E_{\text{absorbed}} \)

- \( E \ldots \text{Incident Energy} \ [\text{W}] \)

- \( 1 = \frac{E_r}{E_i} + \frac{E_t}{E_i} + \frac{E_a}{E_i} \)

- \( 1 = R + T + A \)
  - \( \ldots \text{Reflection-coefficient} + \text{Transmission-coefficient} + \text{Absorption-coefficient} \)

=> Material property, independent of incoming radiant energy!
### Basics – Interaction with matter

... and now as a function of wavelength:

<table>
<thead>
<tr>
<th>Wavelength [µ]</th>
<th>Transmittance</th>
<th>Reflectance</th>
<th>Absorption</th>
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<tr>
<td>0.4</td>
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<td>0</td>
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<tr>
<td>0.8</td>
<td>80</td>
<td>20</td>
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<tr>
<td>1.2</td>
<td>60</td>
<td>40</td>
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<td>1.6</td>
<td>40</td>
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<td>2.0</td>
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<td>2.8</td>
<td>0</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

Percent

Wavelength [µ]
Basics – Interaction with matter

Physical Basics - Absorption

- Nucleus
- Orbital
- Electron
Electron transfer:

- Quantized: $\Delta Q = h \cdot f$
- Occur normally $< 1 \mu m$
- Rarely detected due to mineral composition => complex overlay of absorption features

Vibration modes: Bending & Stretching:

- „Sharper“ and frequent ($3N$ possible for molecules with $N$ atoms)
- Occur normally $>1 \mu m$
- Many fundamentals per material, normally $> 3 \mu m$
- Resonance (combinations & harmonics)
Physical Basics - Absorption

Example: Liquid Water H$_2$O  (Note: different for water vapor!)

- **Fundamentals**
  - $\lambda_1$: 3.106 μm  symmetric OH - stretch
  - $\lambda_2$: 6.080 μm  HOH - bend
  - $\lambda_3$: 2.903 μm  asymmetric OH - stretch

- **Harmonics**
  - $(2 \times f \text{ resp. } \frac{1}{2} \times \lambda)$
    - 1.553 μm
    - 3.040 μm
    - 1.452 μm

- **Combinations**
  - 1.87 μm  $(1/\lambda_3 + 1/\lambda_2)$
  - 0.962 μm  $(1/2 \times \lambda_1 + 1/\lambda_3)$

Fig.: ELACHI
Physical Basics - Absorption

Example: Liquid Water $\text{H}_2\text{O}$  
(Note: different for water vapor!)

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  - $(2^* f \text{ resp. } \frac{1}{2}^* \lambda)$
    - 1.553 $\mu$m
    - 3.040 $\mu$m
    - 1.452 $\mu$m

- **Combinations**
  - 1.87 $\mu$m  $(1/ \lambda_3 + 1/ \lambda_2)$
  - 0.962 $\mu$m  $(1/2^* \lambda_1 + 1/ \lambda_3)$
Beer-Lambert law (base for transmittance spectroscopy):

• Transmittance $t = I / I_0$
• $\log_{10}(I_0/I) = kcI = A$
  A…absorbance
  k…molecular absorption coefficient for molecule species
  c…concentration of absorbing molecules
  I…path length through sample
  ➔ Absorbance ~ molecule concentration

• Also valid for reflectances:
  $A \sim \log_{10} \left( \frac{1}{\rho} \right)$
4th: Sensor
• Input: At-sensor radiance ("Amount of light")
  • Sensor
• Output: DN (Digital Number)

Power at Sensor [W]
Detector Area [m²]
Solid Angle [sr]

<table>
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<th>0</th>
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Sensor Model

- Input: At-sensor radiance
  - (Scanner-Mechanics)
  - Optics inclusive Filter & Dispersion
  - Detectors
  - Electronics
  - A/D
  - Platform Motion & Attitude
- Output: DN
Sensor Model

$L = c_0 + c_1 \cdot DN$

linear region
Focus: Atmospheric Correction
Atmospheric Transmittance
(Solar & Thermal Spectral Region)
Radiative Transfer

first: flat terrain, simplified
Radiative Transfer (flat terrain)

\[ L = c_0 + c_1 \text{DN} \]
Sensor calibration:

\[ L_{\text{Sensor}} = c_0 + c_1 \times \text{DN} \]
Sensor calibration:

\[ L_{Sensor} = c_0 + c_1 \times DN \]

At-sensor radiance:

\[ L_{Sensor} = L_1 + L_2 + L_3 \]

\[ L_{Sensor} = L_{path} + L_{reflected} + L_{adjacency} \]
Radiative Transfer (flat terrain)

Sensor calibration:

\[ L_{\text{Sensor}} = c_0 + c_1 \times \text{DN} \]

At-sensor radiance:

\[ L_{\text{Sensor}} = L_1 + L_2 + L_3 \]

\[ L_{\text{Sensor}} = L_{\text{path}} + L_{\text{reflected}} + L_{\text{adjacency}} \]

Target radiance:

\[ L_{\text{reflected}} = \rho \times E_g \times \frac{\tau}{\pi} \]

\[ E_g : \text{global flux} \quad \tau : \text{total atm. transmittance} \quad \rho : \text{target reflectance} \]
When neglecting the adjacency effect:

\[ L_{\text{Sensor}} = L_{\text{path}} + L_{\text{reflected}} = L_{\text{path}} + \rho \ E_g \ * \ \frac{\tau}{\pi} = c_0 + c_1 \ * \ \text{DN} \]
Radiative Transfer (flat terrain)

When neglecting the adjacency effect:

\[ L_{\text{Sensor}} = L_{\text{path}} + L_{\text{reflected}} = L_{\text{path}} + \rho \cdot E_g \cdot \frac{\tau}{\pi} = c_0 + c_1 \cdot DN \]

Now solving for the target reflectance:

\[ \rho = \frac{\pi ((c_o + c_1 \cdot DN) - L_{\text{Path}})}{\tau \cdot E_g} \]

This means:

- Estimates of the main atm. parameters (aerosol type, optical thickness and water vapor) required for \( L_{\text{path}} \), \( E_g \) and \( \tau \)
- Accurate sensor calibration is mandatory
Radiative Transfer (flat terrain)

Adding details:

\[ E_g = E_{direct} + E_{diffuse} \]

\[ \tau = \tau_{direct} + \tau_{diffuse} \]

And adding adjacency effects:

\[ L_{Sensor} = L_{path} + \rho \ E_g \tau \left( \frac{1}{\pi} \right) \ast \left( \frac{1}{1 - \rho \ s} \right) \]

where \( \rho \): background reflection

\( s \): spherical albedo (atm. backscattering to ground)
Radiative Transfer (flat terrain)

... and all wavelength & angular dependent:

\[ L = L_p(\lambda, z) + \frac{\tau(\lambda, z) E_g(\lambda, z) \rho(\lambda) / \pi}{1 - \bar{\rho}(\lambda) s(\lambda, z)} \]
Absorption and Scattering

Major absorbers in the earth’s atmosphere:

Water vapor, CO₂, O₂, O₃, CH₄

Scattering: molecular (Rayleigh, mostly N₂, O₂) and aerosol

Physical characteristics of aerosols:

size distribution, refractive index

Optical characteristics:

scattering & extinction coefficient

scattering phase function
Absorption and Scattering

Beer’s law

\[ \tau(\lambda, x) = \exp[-\gamma(\lambda) x] \]

homogeneous path

\( \gamma(\lambda) \)  
Extinction coefficient (km\(^{-1}\))

\( x \)  
Path length

\[ \tau(\lambda, x) = \exp\left[ -\int_{0}^{x} \gamma(\lambda, x') \, dx' \right] \]

heterogeneous path
Absorption and Scattering

Beer’s law

\[ \tau(\lambda, x) = \exp[-\gamma(\lambda) x] \]

\( \gamma(\lambda) \)  Extinction coefficient (km\(^{-1}\))
\( x \)  Path length

\[ \xi = \gamma x \]  Optical thickness

homogeneous path
Beer’s law

\[ \tau(\lambda, x) = \exp[-\gamma(\lambda) x] \]

**homogeneous path**

\( \gamma(\lambda) \)  
Extinction coefficient (km\(^{-1}\))

\( x \)  
Path length

**Extinction = Absorption + Scattering**

\[ \gamma(\lambda) = k(\lambda) + \sigma(\lambda) \]
Absorption and Scattering

Beer’s law

\[ \tau(\lambda, x) = \exp[-\gamma(\lambda) x] \]

homogeneous path

\( \gamma(\lambda) \) Extinction coefficient (km\(^{-1}\))

\( x \) Path length

Extinction = Absorption + Scattering

\[ \gamma(\lambda) = k(\lambda) + \sigma(\lambda) \]

Separate: M = Molecule (Rayleigh)

A = Aerosol

\[ \gamma(\lambda) = k_M(\lambda) + k_A(\lambda) + \sigma_M(\lambda) + \sigma_A(\lambda) \]
Absorption and Scattering

Beer’s law

$$\tau(\lambda, x) = \exp[-\gamma(\lambda) x]$$

homogeneous path

$$\gamma(\lambda)$$ Extinction coefficient (km$^{-1}$)

$$x$$ Path length

Extinction = Absorption + Scattering

$$\gamma(\lambda) = k(\lambda) + \sigma(\lambda)$$

Single scattering albedo

$$\omega(\lambda) = \sigma(\lambda) / \gamma(\lambda)$$
Scattering

\[ \sigma_A = \text{const} \lambda^{-n} \]
\[ n = 0.5 - 1.5 \]

\[ \sigma_M = \text{const} \lambda^{-4} \]
Aerosol: strong forward scattering peak

Rel. humidity = 70%, 550 nm

Maritime Aerosol, Rel. humidity=80%
Fig. 8.2  Angular dependence of single-scattering phase functions in any azimuthal plane. The isotropic and Rayleigh functions have been multiplied by 10. (After LaRocca and Turner, 1975.)
Koschmieder Equation:

\[
VIS = \frac{1}{\gamma} \ln \left( \frac{1}{\varepsilon} \right) = \frac{3.912}{\gamma}
\]

Visibility, meteorological range

Contrast threshold \( \varepsilon = 0.02 \)

Extinction coefficient \((\gamma \text{ at } 0.55 \mu m)\)

(dependents on complex refractive index, particle size & distribution, concentration)

Wavenumber \( w \) (cm\(^{-1}\)) and wavelength \( \lambda \) (\(\mu m\))

\[
w(\text{cm}^{-1}) = \frac{10^4}{\lambda(\mu m)}
\]
Scattering and Absorption

Top: L-5 TM bands 1-3
(480, 560, 660 nm)

Bottom: TM bands 4, 6
(840 nm, 11.5 µm)

Note: TIR affected by WV, not by dust particles
Radiative Transfer (flat terrain)

\[ L = L_p(\lambda, z) + \frac{\tau(\lambda, z) E_g(\lambda, z) \rho(\lambda)/\pi}{1 - \bar{\rho}(\lambda) s(\lambda, z)} \]

1: path radiance: scattered photons
2: reflected radiance
3: adjacency radiance (reflected & scattered)
Adjacency Effect

Largest for high reflectance contrast and short wavelength blue-green spectral region: contrast usually small

NIR: large reflectance contrast vegetation/water and land/water

Low pass filter effect, blurring of spatial contrast, typical range 1 km

Adjacency correction removes blurring, improves contrast

\[ L = L_0 e^{-\frac{r}{r_s}} \]

\[ \rho_t = \rho_0 + q (\rho_0 - \bar{\rho}) \]
\[ \rho_t = 5 + 0.114 (5 - 40) \]
\[ \rho_t = 5 - 4 = 1\% \]

\( \bar{\rho} = 40\% \) Vegetation

\( \rho_0 = 5\% \) Lake

Vegetation

Vegetation

Land

Water
Adjacency Effect

Example:

\[ \rho_f = \rho_{\text{lake}} = 1\% \]
\[ \bar{\rho} = \rho_{\text{vegetation}} = 40\% \]
\[ \rho_0 = \rho_{\text{lake, sensed}} = 5\% \]

q: scaling factor, based on ratio \( \tau_{\text{direct}} : \tau_{\text{diffuse}} \)

\[ \rho_f = \rho_0 + q (\rho_0 - \bar{\rho}) \]
\[ \rho_f = 5 + 0.114 (5 - 40) \]
\[ \rho_f = 5 - 4 = 1\% \]
Radiative Transfer (mountainous terrain)

Additional radiation component from opposite mountains

weighted with view factor \( V(\text{terrain}) = 1 - V(\text{sky}) \)

(only important for steep terrain)
6. Radiative Transfer Codes
Radiative Transfer Codes

ATCOR uses MODTRAN-5 (v3r1) / HITRAN 2012
Developed by: Spectral Sciences Inc & Air Force Research Lab, USA
Spectral range : \[0 - 50,000 \text{ cm}^{-1} \ (0.25 - 14 \mu \text{m})\]
Spectral resolution: \[1 \text{ cm}^{-1} \ (0.1 \text{ nm at } 1 \mu \text{m})\]
Multiple scattering algorithms: Isaacs 2 stream, DISORT 8/16 streams
Scaled DISORT, correlated k for high accuracy
Coupled treatment of absorption and scattering
7. The ATCOR Approach
Overall Workflow

Read LUTs

Masking haze, clear, cloud, water, shadow

haze removal

cirrus removal

shadow removal

DDV algorithm, VIS map bands (Red, SWIR) or (Red, NIR) visibility index vi & AOT

Update Lp (visible bands) if blue band exists and ratio_blu_red > 0

Water Vapor Map (wv) (if required bands exist) Update LUT = LUT(wv)

Iterative reflectance retrieval (incl. adjacency and spherical albedo)

Spectral polishing

BRDF correction
DDV (dense dark vegetation) pixels

Detection: $1\% < \rho(2.2\ \mu m) < 5\% $ (atm: VIS=23 km)

$1\% < \rho(1.6\ \mu m) < 10\% $ (atm: VIS=23 km)

and exclude water with NDVI > 0.1

Correlation (2.2 $\mu$m band)
$\rho($red$)=0.5 \times \rho(2.2\ \mu m)$
$\rho($blue$) = 0.5 \times \rho($red$)$

Correlation (1.6 $\mu$m band)
$\rho($red$)=0.25 \times \rho(1.6\ \mu m)$
$\rho($blue$) = 0.5 \times \rho($red$)$
DDV (dense dark vegetation) pixels

Detection: $1 \% < \rho(2.2 \mu m) < 5 \%$ (atm: VIS=23 km)

$1 \% < \rho(1.6 \mu m) < 10 \%$ (atm: VIS=23 km)

and exclude water with NDVI > 0.1

Adjustment of empirical correlation factor 0.5 possible (i.e., to season, biome)

Correlation (2.2 $\mu$m band)

$\rho(\text{red}) = 0.5 \times \rho(2.2 \mu m)$

$\rho(\text{blue}) = 0.5 \times \rho(\text{red})$

Correlation (1.6 $\mu$m band)

$\rho(\text{red}) = 0.25 \times \rho(1.6 \mu m)$

$\rho(\text{blue}) = 0.5 \times \rho(\text{red})$
AOT / Visibility Retrieval

VIS / AOT evaluated with red spectral band

\[ L = L_p + \tau \rho_{\text{ref, red}} E_g / \pi \]

1) \( \rho_{\text{ref, red}} \) known by empirical relation from \( \rho_{\text{ref, SWIR}} \)
2) \( E_g, \tau, L_p \) calculated as function of VIS
3) Fit of resulting curve with L measure results in VIS
VIS / AOT evaluated with red spectral band

\[ L = L_p + \tau \rho_{ref} \frac{E_g}{\pi} \]

- modelling, atm. LUT, sun geometry
- measurement

Visibility (km)
1. For DDV pixels: \( \rho_{\text{reflected, blue & red}} \) is known from spectral correlation with \( \rho_{\text{SWIR}} \)

2. Calculate path radiance \( L_p(\text{blue}) \), \( L_p(\text{red}) \) by \( L_{\text{path}} = L_{\text{sensor}} - L_{\text{reflected}} \)

3. Calculate double ratio of \( L_p(\text{scene}) \) to \( L_p(\text{MODTRAN}) \) for standard aerosol types: rural, urban, maritime, desert

4. Select aerosol with closest match to one of the standard types \( \text{Ratio} = 1 \)

\[
\text{Ratio} = \frac{L_p(\text{blue}, \text{scene}) / L_p(\text{red}, \text{scene})}{L_p(\text{blue}, \text{MODTRAN}) / L_p(\text{red}, \text{MODTRAN})}
\]
Water Vapor Retrieval

APDA (Atm. Precorrected Differential Absorption) algorithm

Water absorption depth exponentially correlated with WV

Minimum: 2 channels (extrapolation),
Better performance: APDA-LIRR (linear regression ratio) \( n \geq 3 \) channels

\[
R = \frac{L_2(\rho_2, u) - L_{2p}(u)}{w_1\{L_1(\rho_1, u) - L_{1p}(u)\} - w_3\{L_3(\rho_3, u) - L_{3p}(u)\}} = \exp(-\alpha + \beta \sqrt{u})
\]

\[
u = \left(\frac{\alpha + \ln\{R\}}{\beta}\right)^2
\]
Water Vapor Retrieval

APDA (Atm. Precorrected Differential Absorption) algorithm

Water absorption depth exponentially correlated with WV

Minimum: 2 channels (extrapolation),
Better performance: APDA-LIRR (linear regression ratio) $n \geq 3$ channels

Note:
Targets must not have water absorption (i.e., no vegetation!)

$$u = \left( \frac{\alpha + \ln\{R\}}{\beta} \right)^2$$
Problems:
1. Lambertian Cos - Law overestimates topographic influence in steep terrain
2. Bidirectional reflectance behavior especially pronounced in steep terrain
3. BRDF surface cover dependent

Illumination angle =
Local solar zenith $\beta$:
$$\cos \beta = \cos \theta_s \cos \alpha - \sin \theta_s \sin \alpha \cos(\phi_s - \phi)$$
Problem with cos correction

Simplified:

\[ \rho(\text{horizontal}) = \rho(\text{slope}) \frac{\cos \theta_s}{\cos \beta} \]

\[ \beta \to 90^\circ \Rightarrow \cos \beta = 0 \Rightarrow \rho(h) \to \infty \]

Better: also include \( E(\text{diffuse}) \)
But: problem \( \cos \beta \to 0 \) remains
i.e. overcorrection

\[ \rho = \frac{\pi (L - L_p)}{\tau_v \left( \tau_s E_s \cos \beta + E_{\text{dif}} + E_{\text{terrain}} \right)} \]
Topographic Correction Methods (3)

Lambertian

\[ \rho(\text{horizontal}) = \rho(\text{slope}) \frac{\cos \theta_s}{\cos \beta} \]

Non-Lambertian

Minnaert

\[ \rho(\text{horizontal}) = \rho(\text{slope}) \left[ \frac{\cos \theta_s}{\cos \beta} \right] K_i \]

\[ \ln(\rho_{\text{slope}}) = \ln(\rho_{\text{hor}}) + K_i \ln \left( \frac{\cos \beta}{\cos \theta_s} \right) \]

C correction (empirical-statistical)

\[ \rho(h) = \rho(\text{slope}) \frac{\cos \theta_s + c_i}{\cos \beta + c_i} \]

\[ c_i = m_i / b_i \quad m_i : \text{slope} \quad b_i : \text{offset} \]

Linear scene-based regression

\[ \rho(\text{slope}) = b_i + m_i \cos \beta \]
Topographic Correction Methods (4)

Empirical-statistical correction functions
Topographic Correction Methods (5)

Lambert correction  Illumination $\beta(x,y)$  Empirical geometric correction

Empirical correction starts at a threshold angle $\beta_T > \theta_s$ and reduces reflectance:

$$\rho(\text{corrected}) = \rho(\text{Lambert}) G$$
Topographic Correction Methods (5)

Lambert correction  Illumination $\beta(x,y)$  Empirical geometric correction

ATCOR uses empiric method

Default–threshold $\beta_T$ if $\beta > \text{SolarZenith} + 20^\circ$

i.e., only for critical SolarZenith, and also preventing topo.correction

on shallow slopes
Additional BRDF Correction – BREFCOR
• Shadow: direct solar beam is completely or partially attenuated
• Diffuse solar flux is still being reflected from ground
• Ratio diffuse-to-direct solar flux on ground depends on wavelength
• Retrieve missing fraction of direct solar irradiance

Use channels from NIR (800 nm) to SWIR (2500 nm)
most sensitive, low diffuse, high direct solar radiation if no shadow

Ratio of direct solar flux to total flux (direct + diffuse)

top: visibility 50 km
bottom: visibility 23 km
De-Shadowing
Main Processing Steps

Interactive process:
1) Set threshold for shade / no-shade in histogram
   $\Rightarrow$ core shadow area
2) Extend for outer shadow areas in order to prevent borders

- unscaled shadow function $\Phi$ (eq. 4)
- scaled shadow function $\Phi^*$ (eq. 5)
- threshold $\Phi_T$: core shadow areas
- expand shadow mask
- de-shadowing with $\Phi^*$ (eq. 6)
De-Shadowing
Main Processing Steps

1. surface reflectance (eq. 1)
2. exclude water & cloud (eq. 1a,b)
3. matched filter vector (eq. 3)
4. unscaled shadow function $\Phi$ (eq. 4)
5. scaled shadow function $\Phi^*$ (eq. 5)
6. threshold $\Phi_T$: core shadow areas
7. expand shadow mask
8. de-shadowing with $\Phi^*$ (eq. 6)
De-Shadowing Equation

\[
\rho_i(x, y) = \frac{\pi \left( d^2 \{ c_0(i) + c_1(i) DN_i(x, y) \} - L_{p,i} \right)}{\tau_i \left( E_{dir,i} \Phi^*(x, y) + E_{dif,i} \right)}
\]

(6)

Core shadow areas important otherwise a lot of misclassified shadow pixels occur.
De-Shadowing

De-Shadowing Method: without / with core sh. areas
De-Shadowing

ATCOR : Example of Cloud Shadow Removal

HyMap scene, Chinchon, Spain, 12 July 2003, RGB=878, 646, 462 nm

Ref: Richter & Mueller, 2005
De-Shadowing

Example: Multispectral Satellite Data, Ikonos

Example of building shadows

Ikonos Munich, 17 Sept. 2003, RGB=bands 4/3/2
Courtesy of European Space Imaging / © European Space Imaging GmbH
Conclusions

Current limitations:

• method can be applied fully automatic, but

• some thresholds are being used, therefore best results obtained in interactive mode

• approach works with at least 2 bands (red, NIR), but performance is better if some SWIR bands (1.6, 2.2 µm) are available

• if percentage of shadow pixels in the image is very small or shadow areas are located in a small sub-image, better results are usually obtained by processing of the sub-image (⇒ histogram-based approach)

• water pixels may escape the water mask, then these pixels might be included in the shadow map. Upon correction, these water pixels will appear very bright.
Haze Removal

De-hazing result:
Landsat-5 TM

- Method requires: clear and hazy areas.
- Method fails, if percentage of clear areas is small (haze and cloud areas dominate).
- Method fails if correlation coefficient between red and blue band is low ($r < 0.8$).
- Algorithm can also be applied for sensors without a blue band, but with a green band, with a reduced performance.
- Not appropriate for haze over water.
Cirrus (path radiance) corrected image:

\[ \rho(\lambda) = \rho^*(\lambda) - \rho_c^*(1.38 \mu m) / \gamma \]
Approach: carry out multiple atmospheric corrections, thereby shift channel center wavelengths until reflectance spectrum shows minimum deviations with respect to smoothed spectrum.

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Inflight Radiometric Calibration

\[ L(i) = c_0(i) + c_1(i) \cdot DN(i) \]

- Sensor
- Ref. Targets
- Measurement of Atm.
- Ground Spectrometer \( \rho(\lambda) \)

- Calculated Radiance \( L_T(i) \)

\[ L_T(i) = \int \frac{R_i(\lambda) \cdot L_T(\lambda) \, d\lambda}{\int R_i(\lambda) \, d\lambda} \]

- RT Code \( L_T(\lambda, \rho, \theta_S, \theta_V, \phi) \)

- Calibration: \( c_0(i), c_1(i) \)

- Spatial Model
- Target \( DN_T^{image} \Rightarrow true \ DN_T \)
- Background
- adjacency effect
- PSF

Radiative Transfer Model

Spatial Model
Solar Irradiance Spectra

Previously: Kurucz 1997
(used by MODTRAN)

Now also
Kurucz 2005
Standard: Fontenla et al 2009, 2011 (i.e., “low activity sun”)