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Atmospheric correction of APEX hyperspectral data

Abstract

Atmospheric correction plays a crucial role among the processing steps applied to remotely sensed hyperspectral data. Atmospheric correction comprises a group of procedures needed to remove atmospheric effects from observed spectra, *i.e.* the transformation from at-sensor radiances to at-surface radiances or reflectances. In this paper we present the different steps in the atmospheric correction process for APEX hyperspectral data as applied by the Central Data Processing Center (CDPC) at the Flemish Institute for Technological Research (VITO, Mol, Belgium). The MODerate resolution atmospheric TRANsmission program (MODTRAN) is used to determine the source of radiation and for applying the actual atmospheric correction. As part of the overall correction process, supporting algorithms are provided in order to derive MODTRAN configuration parameters and to account for specific effects, *e.g.* correction for adjacency effects, haze and shadow correction, and topographic BRDF correction. The methods and theory underlying these corrections and an example of an application are presented.

Keywords

Hyperspectral • atmospheric correction • automatic workflow • reflectance • APEX • MODTRAN

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Introduction

In order to use hyperspectral imaging data for the quantitative remote sensing of land or water surfaces, atmospheric effects must be removed. Atmospheric correction is essential for converting radiance measured by the sensors to surface reflectance. Atmospheric correction algorithms can be roughly divided into scene-based empirical approaches, and the more complex methods based on radiative transfer modelling. The radiative transfer modelling approaches are now sufficiently mature for routine processing of hyperspectral image data (Gao et al. 2006).

A range of radiative transfer based atmospheric correction methods for land have been developed for hyperspectral imaging data over the years. Common methods developed for land include ATREM (Atmosphere REMoval), HATCH (High Accuracy ATmospheric Correction for Hyperspectral data), ISDAS (Imaging Spectrometer Data Analysis System), ACORN (Atmospheric CORrection Now), FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) and ATCOR (ATmospheric CORection) (for a detailed overview see Gao et al. 2009). The last three are based on the MODTRAN radiative transfer code.

For water targets the theory of atmospheric scattering and absorption is similar to that for land targets but with one important exception: for water targets the 'non-lambertian' air-water interface is an extra complication. Photons that are reflected by the air-water interface have not interacted with the water and its constituents, and thus represent an unwanted signal that must be removed. A correction for the air-water interface reflection is required in order to derive the so called "water leaving reflectance" from hyperspectral imaging data.

One of the earliest operational codes for atmospheric correction of hyperspectral data over water surfaces is the TAFKAA code developed by the U.S. Naval Research Laboratory (Gao et al. 2000; Montes and Gao 2004). TAFKAA is based on the earlier ATREM code of Gao and Goetz (1990) and uses the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) for its scattering calculation. The Modular Inversion Program (MIP) (Heege et al. 2005) includes different modules to derive the bio-physical parameters by inverting the measured radiance signal at the sensor. Inverted parameters include, for example, the sub-surface reflectance, the concentration of water constituents and aerosol information. The C-Wombat-C (Coastal Waters and Ocean MODTRAN-4 Based ATmospheric Correction) code (Brando and Dekker 2003) follows the modelling described in de Haan and Kokke (1996) and has been widely applied to a series of hyperspectral airborne and space borne sensors (Giardino et al. 2007; Brando et al. 2009).

In support of recurrent hyperspectral airborne campaigns (http://campaigns.vgt.vito.be/) VITO has developed a dedicated Central Data Processing Center (CDPC). Continuously developed, improved and validated, it has served for a long time as a processing platform for a wide variety of sensor types: multispectral and hyperspectral sensors, line and frame scanners, and airborne and spaceborne instruments. APEX data has been processed at the CDPC since the start of the operational phase (2010).

Within the CDPC, the MODTRAN4 Radiative Transfer Code (RTC) (Berk et al. 1999) is used to determine the sources of radiation and the MODTRAN4 interrogation technique

(Verhoef & Bach 2003; De Haan & Kokke 1996; Liang, Fang & Chen 2001) is used for applying the actual atmospheric correction, *i.e.* the transformation from at-sensor radiance to at-surface radiance or reflectance. The CDPC atmospheric correction has been benchmarked over land against the commercially available ATCOR-4 atmospheric correction program (Schläpfer et al. 2008).

The MODTRAN4 based correction converts the at-sensor radiance to Hemispherical-Directional Reflectance Factor (HDRF) values for land targets. For water targets, in a similar way to the C-Wombat-C code, the CDPC includes a sky glint correction to derive the so called "water leaving reflectance".

As part of the overall atmospheric correction process additional algorithms are included to account for specific effects:

- Correction for adjacency effect,
- Haze and shadow correction,
- Topographic BRDF correction.

Following this set of corrections, the resulting land product is still an HDRF product. The VITO Central Data Processing Center contains kernel BRDF correction algorithms to produce Bidirectional Reflectance Factor (BRF) and Nadir BRDF-Adjusted Reflectance (NBAR) products. Some further testing across a range of scenes is, however, needed before the BRDF corrections can be used in the nominal operational atmospheric correction process for APEX data. The default APEX reflectance products are HDRF land surface reflectances, and water leaving reflectances.

The atmospheric correction module

The MODTRAN interrogation technique

The radiance received by the sensor (L_{sensor}) consists of the atmospheric path radiance ($L_{\mathrm{atm-path}}$), the background path radiance ($L_{\mathrm{backgr-path}}$) and the target radiance L_{target}; or:

$$L_{sensor} = L_{\mathrm{atm-path}} + L_{\mathrm{backgr-path}} + L_{\mathrm{target}}$$

Only L_{target} contains information from the pixel on the ground:

$$L_{\mathrm{target}} = \frac{t_{\mathrm{dir}}(\tau,\theta_{\mathrm{v}})t(\theta_{\mathrm{s}})\rho_s F_0 \cos(\theta_{\mathrm{s}})}{\pi(1 - s * \rho_s)}$$

where: ρ_s is the surface reflectance, F_0 is the extraterrestrial solar irradiance, θ_{s} and θ_{v} are the sun and view zenith angles respectively, t_{dir} is the direct ground-to-sensor transmittance, t_{dir} is the total sun to surface transmittance, and τ is the optical depth of the atmosphere.

For a specific ground albedo spectrum, MODTRAN calculates:

- the total at-sensor radiance (L_{sensor}),
- the ground radiance (*i.e.* the target radiance L_{target} or L_{ground}),
- the at-sensor radiance scattered into the path by the atmosphere and surrounding targets (L_{path}) (the path radiance including the diffuse reflected ground radiation, assuming a homogenous surface) (sum of $L_{\mathrm{atm-path}}$ and $L_{\mathrm{backgr-path}}$).

However, MODTRAN cannot directly be inverted to retrieve the surface reflectance ρ_s. Therefore the so called MODTRAN4 interrogation technique is used for atmospheric correction purposes. Within the MODTRAN4 interrogation technique MODTRAN is run for three different surface albedos: 0, 0.5 and 1. This results in a set of path radiances ($L_{\mathrm{path},0.0}$, $L_{\mathrm{path},0.5}$, $L_{\mathrm{path},1.0}$) and ground radiances ($L_{\mathrm{ground},0.0}$, $L_{\mathrm{ground},0.5}$, $L_{\mathrm{ground},1.0}$). From these sets of radiances the surface reflectance (ρ_s) can be retrieved from the at-sensor radiance (L_{sensor}) and the background radiance (L_{backgr}) (*i.e.,* the average radiance received by the neighboring pixels) as:

$$\rho_s = \frac{c_1 + c_2 L_{sensor} + c_3 L_{\mathrm{backgr}}}{c_4 + c_5 L_{\mathrm{backgr}}} \tag{1}$$

where:

$$c_1 = -L_{\mathrm{path},0.0}$$

$$c_2 = 1 + \left(L_{\mathrm{path},0.5} - L_{\mathrm{path},0.0}\right) / L_{\mathrm{ground},0.5}$$

$$c_3 = 1 - c_2$$

$$c_4 = (1 - c_5)(L_{\mathrm{ground},1.0} + L_{\mathrm{path},1.0} - L_{\mathrm{path},0.0}) + (c_5 c_1)$$

$$c_5 = \left(2L_{\mathrm{ground},0.5} - L_{\mathrm{ground},1.0}\right) / \left(L_{\mathrm{ground},0.5} - L_{\mathrm{ground},1.0}\right)$$

For inland and coastal water scenes the water-leaving reflectance is retrieved from the surface reflectance as:

$$\rho_{\mathrm{w}} = \rho_{\mathrm{s}} - d_1 \tag{2}$$

where:

$$d_1 = \pi r(\theta_{\mathrm{v}}) L_{\mathrm{sky}} / E_{\mathrm{d}}$$

An estimation of the d_1 parameter, in order to retrieve water leaving reflectance, requires two MODTRAN4 runs: one with the sensor looking at the sky for L_{sky} and the other at the surface for E_{d}.

The parameters ($c_{1,\dots,5}$, d_1) depend on spectral, geometric and atmospheric parameters: *e.g.* viewing and illumination geometry, flight/ground altitude, aerosol density/visibility, water content and aerosol type.

Atmospheric Correction supporting modules

In Figure 1 a flowchart is presented showing the different modules used in the operational atmospheric correction of APEX. These modules are described in more detail in the following sections.

Orthorectification module

An orthorectification module is implemented at VITO for a full characterization of viewing and illumination geometry. The orthorectification module returns the following information for each pixel: X, Y coordinates (in the preferred projection system), ground altitude, sun/view zenith and azimuth angles (degrees), illumination angle (degrees), view path length (meters) and the sky view factor. All these parameters are used as inputs for the MODTRAN atmospheric correction module.

A detailed description of the orthorectification module is provided in an article about the geometric correction of APEX hyperspectral data (Kristin Vreys et al) elsewhere in this journal.

Wavelength shift detection module

Spectral calibration parameters (*i.e.* central wavelength and bandwidth (expressed as FWHM)) are initially derived from the pre-flight laboratory calibration at the Calibration Home Base (CHB) (DLR 2015). However, in-flight wavelength shifts occur due to vibration effects and pressure/temperature variations. Therefore, prior to the atmospheric correction, a spectral shift detection is applied to the APEX data. The applied spectral shift detection approach is a modified version of the method originally presented by Gao, Montes & Davis (2004) using a series of solar or terrestrial atmospheric features present in the APEX data. In general the method first performs a column averaging of

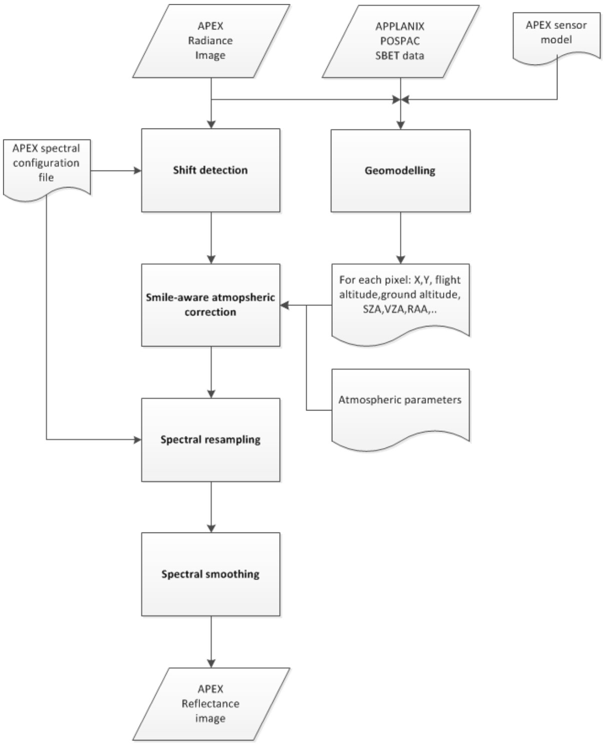

Figure 1. APEX atmospheric correction flowchart

the calibrated APEX radiance image. A set of spectrally shifted reference radiances are then calculated with MODTRAN as follows: first, a reference at-sensor radiance spectrum (L^{Model}) is calculated at a fine spectral resolution; L^{Model} is then convoluted with the APEX spectral response functions as:

$$L^{k,Model} = \int L^{Model} SRF_k(\lambda) d\lambda \,/\, \int_0^\infty SRF_k(\lambda) d\lambda$$

This spectral resampling is repeated for a series of spectrally shifted response functions:

$$L^{k,Model}_{\Delta\lambda} = \int L^{Model} SRF_k(\lambda + \Delta\lambda) d\lambda \,/\, \int_0^\infty SRF_k(\lambda + \Delta\lambda) d\lambda$$

A continuum removal across the atmospheric feature is applied to both the image and the reference radiance spectra (generated with MODTRAN) and finally an evaluation of a merit function is done to determine the wavelength shift. The algorithm does not need ground reflectance measurements to derive the wavelength shift parameters but relies only on the measured at-sensor radiance data.

The nominal bandwidth is assumed to remain constant. The inversion of two parameters (*i.e.* both the central wavelength and the bandwidth) would be difficult as the number of spectral bands covering the absorption feature might be insufficient.

Atmospheric composition

The atmospheric parameters at the time of the flight can be manually fixed or computed from the images themselves. In most cases ground teams are mobilized during APEX flights who have the goal of measuring atmospheric parameters (by means of ground-based sunphotometers) and reference ground spectra. The most important configurable parameters are the atmospheric water vapor content (g/cm^2), visibility (km) (or Aerosol Optical Depth at 550nm) and the aerosol type (such as rural, urban, maritime). All these parameters are inferred from the sunphotometer measurements, if available.

In case no ground measurements are performed during the flights, CDPC employs automatic algorithms for parameter retrieval. For water vapor retrieval, CDPC uses the methodology presented by Rodger & Lynch (2001), while the algorithm described by Richter, Schläpfer & Müller (2006) is used for automatic visibility retrieval.

Spectral resampling module

APEX is known to have some smile effects, *i.e.* the central wavelength depends slightly on the column pixel location. These smile effects are taken into account during the atmospheric correction. After the atmospheric correction, the reflectance data is resampled to the wavelength of the center pixel as measured during the sensor spectral calibration on the Calibration Home Base (CHB). This spectral resampling is automatically performed in the CDPC.

Spectral Smoothing module

As the reflectance spectra retrieved from the APEX instrument might have some spectral artifacts, which are visible as high frequency spikes, a wavelength dependent spectral smoothing of the data might be required. These spectral artifacts have various causes as outlined by Schläpfer & Richter (2011), for example: spectral mis-calibration, spectral instability, errors in the atmospheric absorption, uncertainties in the solar reference spectrum, intrinsic variation of the atmosphere and the sun, statistical photon shot noise, detector readout inconsistencies, peculiar readout noise in the detector electronics, etc. Smoothing of the APEX reflectance spectra is done using the semi-interactive smoothing application, developed in-house. The application is part of VITO's Colibri ENVI/IDL open source code library, which has been made available to the science community (http://lemon.vgt.vito.be/content/tools). The smoothing algorithm is based on the weighted mean of the spectral values of neighboring wavelengths. With the semi interactive smoothing algorithm it is possible to subdivide the spectrum into discrete groups of wavelengths for which individual smoothing factors can be defined. In this way it is possible to preserve important or fine details of the spectrum, while other parts can be treated less carefully.

Auxiliary options

In support of the atmospheric correction, several additional options can be activated in the CDPC: correction of adjacency effects, and use of topographic and kernel BRDF corrections.

Adjacency correction

The adjacency effects refer to the contribution of background (L^{rs}_{backgr}) to the observed spectrum through scattering. In the CDPC, the size of a spatial kernel can be introduced to define the spatial extent of the pixels potentially contributing to the current observation.

Topographic BRDF correction

An additional topographic correction might be necessary for mountainous areas where slopes oriented to the sun receive more solar irradiance and appear brighter than those facing away from the sun. Different approaches, all using a detailed digital elevation model (DEM) of the scene, exist to correct for the illumination difference (Richter, Kellenberger & Kaufmann 2009). In the CDPC the modified Minnaert (Richter 1998) normalization approach is implemented.

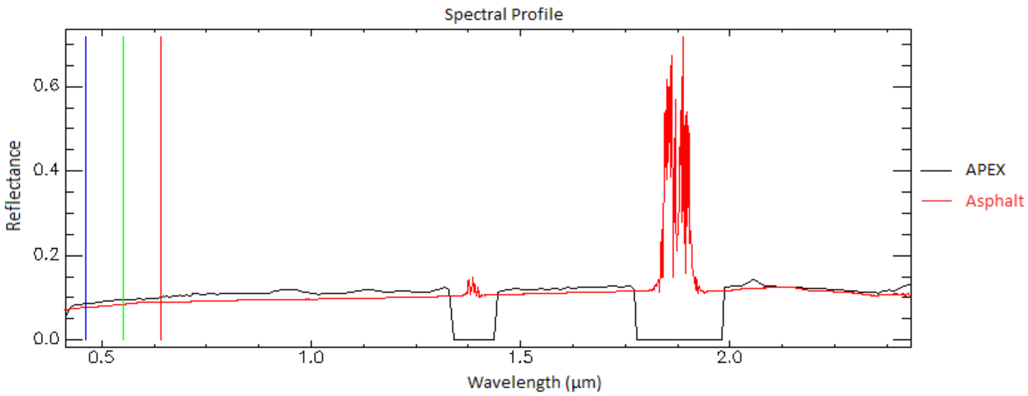

Figure 2. APEX spectrum vs ground reference spectrum (ASD) for an asphalt target

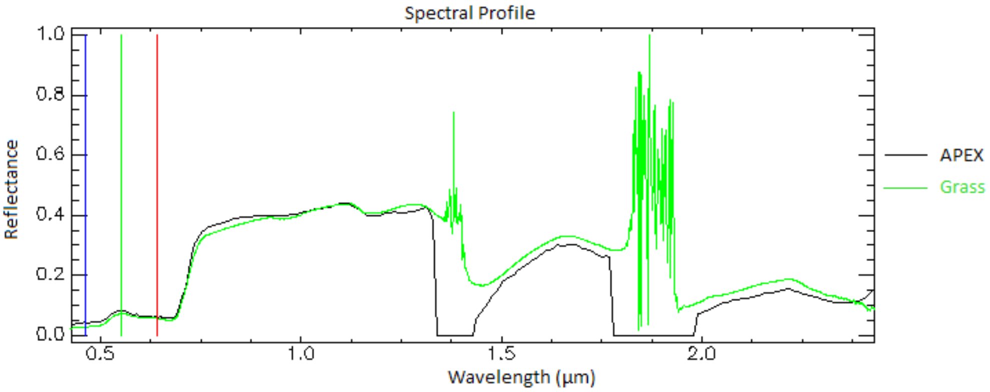

Figure 3. APEX spectrum vs ground reference spectrum (ASD) for a grass target (football field)

Kernel-based BRDF correction

In this BRDF correction technique, a linear combination of kernels is fitted to the reflectance data and then used to normalize the image to standard solar and view angle geometry.

Atmospherically corrected apex spectra

All the algorithmic components in the atmospheric correction process are based on a mixed empirical/physical and theoretical base. As such, atmospheric correction is not an “exact” science. Therefore, the quality of the combined radiometric and atmospheric correction of an APEX image is illustrated by comparison with spectral Ground Control Points (GCPs). A spectral GCP represents a uniform and spectrally time-invariant target of sufficient size compared with the Ground Sampling Distance (GSD) of the sensor system. Figure 2 shows the APEX spectrum of an asphalt pixel (black) together with the corresponding spectrum measured on-ground (red); while in Figure 3 the same comparison is shown for a pixel on a football field. In the APEX spectra presented in the two figures, the reflectance values corresponding to noisy bands around two water absorption features were set to zero.

Conclusion

In this paper, the atmospheric correction module and supporting modules that are implemented in the VITO Central Data Processing Center are presented. The complexity of this procedure and the intrinsic variability of atmospheric parameters require well-established data processing chains and intensive validation and improvement. Moreover, a drawback of the rich information content in hyperspectral data is the large data volume, which means that powerful hardware resources are needed to handle it. The VITO CDPC already has a history of several years, and it was used successfully as a processing platform not only for hyperspectral, but also for (airborne/spaceborne) multispectral data. The flexibility of the processing platform, in combination with the vast experience gained by VITO researchers during the effective operation of the CDPC, and the continuous efforts to update and improve the implemented procedures, confirms the CDPC as a robust and modern tool with a high quality reflectance output, as is illustrated by the examples presented in this work.

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