Atmospheric correction of high resolution multi-spectral satellite images using a simplified method based on the 6S code

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Abstract

A set of high-resolution multi-spectral satellite images were collected and processed to estimate the sediment concentration in the sea-breaking zone. The value of Total Suspended Matter (TSM) is empirically related to the sea surface reflectance. However, in order to obtain accurate reflectance measurements from the satellite images, the effect of the atmosphere needs to be accounted for. A set of satellite images from the SPOT/HRVIR and Terra/ASTER sensors were collected for the study area, a section of the northwest coast of Portugal around Aveiro. The images were atmospherically corrected using a method combining 6S simulations and ground horizontal visibility measurements. The method uses a reference scenario based on the typical values for each image of the following parameters: solar zenith angle, viewing zenith angle, viewing azimuth angle, ground height, and ground horizontal visibility. Some of these parameters are nearly constant for the whole scene. Each of the relevant parameters is allowed to vary within a reasonable range around its reference value. The 6S radiative transfer code is used to generate bottom of the atmosphere reflectance values as a function of the top of the atmosphere recorded reflectances, for each of the parameters. Suitable atmospheric and aerosol models are selected according to the meteorological auxiliary data available. For each pixel in the image, an atmospheric corrected reflectance is obtained as a sum of the individual corrections due to each of the parameters. Sea sand locations were used as test sites for an evaluation of the atmospherically corrected reflectance accuracy.

1 Introduction

Earth observation satellites are increasingly important for environmental monitoring. In order to make quantitative analysis of the Earth's surface, the effect of the atmosphere on the recorded signal needs to be considered. The atmospheric correction of the data allows for reflectance values of the observed target at the Earth's surface to be obtained from the recorded radiance values at the satellite sensor. The visible and near-infrared radiation is affected by the atmosphere through gaseous absorption and scattering by molecules and aerosols and the sun-target-sensor geometry and the surface characteristics need also to be accounted for in order to obtain accurate surface reflectance values (Teillet 1992, Tanré et al. 1992).

The effective application of atmospheric corrections is however a problematic task. The atmosphere composition is highly variable, both temporally and spatially, and the information available about the atmosphere is usually too sparse. Although the topic of radiative transfer in the atmosphere is reasonably well understood, the actual implementation of atmospheric corrections is still complex. Several methodologies have been developed to remove the effect of the atmosphere on the recorded satellite signal. Radiative Transfer Codes (RTC) have been widely used by the remote sensing community for this purpose, such as the 6S code (Second Simulation of the Satellite Signal in the Solar Spectrum, Vermote et al. 1997a) and MODTRAN (Berk et al. 1989). Even if the exact atmospheric profile was known, the computational effort involved in a pixel-by-pixel correction would be too large - especially for large amounts of data, as is usual the case with satellite images. The lack of input atmospheric data available, together with computational burden explains why for many applications atmospheric corrections are still not used (Song et al. 2001).

The development of simple, easy to implement, atmospheric correction strategies is an important issue. Such methods should rely on a limited amount of easily obtainable atmospheric input data and be computationally efficient. An absolute accuracy is not expected from a simple atmospheric correction method, but it should nevertheless provide a more realistic result than using uncorrected data. High spatial resolution sensors such as SPOT/HRVIR (Satéllite Probatoire d'Obsérvation de la Terre / High Resolution Visible and Infrared) or Landsat/TM (Thematic Mapper) are still a very commonly used source of data, which needs to be atmospherically corrected for most applications. Although some of the most recently developed sensors (e.g. ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer) already provide atmospherically corrected data, these datasets are often not available for near real-time applications. Furthermore, for long-term monitoring applications using historic data, sensors like AVHRR, TM and HRV(IR) might be the only available source, and contemporary atmospheric information might be limited to meteorological data.

This paper describes the application of a simple and fast pixel-by-pixel atmospheric correction method to high spatial resolution images. This application results from the preliminary ongoing attempts for the monitoring of the sea breaking zone in the northwest coast of Portugal using high spatial resolution satellite images. The low reflectance values of sea water in the visible and near infrared spectral regions make atmospheric correction an essential processing task, as most of the signal recorded by the sensor is due to the atmosphere. The method relies on a simplified use of the 6S RTC without recourse to multidimensional look-up tables (LUT). It can be used for both present and past data and is also suited for near real time applications. An estimation of the surface (or Bottom Of Atmosphere, BOA) reflectance is made from the signal recorded by the satellite sensor at the Top Of Atmosphere (TOA). The input information required includes a set of ground horizontal visibility values at 0.550µm, and the observation / illumination geometry and target height for each pixel. The ground horizontal visibility values are used by the RTC to estimate the aerosol loading, for a given atmospheric scenario.

2 The 6S radiative transfer code

The Second Simulation of the Satellite Signal in the Solar Spectrum (6S) is a radiative transfer code developed by Vermote et al. (1997a), following earlier versions developed by Tanré et al. (1990). The 6S RTC simulates the effect on the radiation transferred through the Earth's atmosphere in the spectral range 0.25-4.00µm, and also accounts for combined surface-atmosphere effects.

The 6S code allows for the simulation of the signal measured by a satellite sensor. Given the target reflectance of a pixel and the sensor characteristics, the code simulates the effect of the atmosphere in the signal due to scattering by molecules and aerosols, and absorption - mainly by

H_2O, CO_2, O_2, O_3, CH_4, N_2O and CO (Vermote et al. 1997b). The input parameters include the viewing and illumination geometry, atmospheric model for the gaseous components, aerosol model, sensor/band information, and BOA reflectance. The ground horizontal visibility is also an input parameter, used to estimate the optical depth at 0.550 µm due to aerosol loading. The 6S code computes the TOA reflectance amongst other outputs.

The 6S RTC can also be run in the 'atmospheric correction mode', computing in this case the BOA reflectance, given the at-sensor measured value. The input information on atmospheric conditions is the same as in the situation described above, but no BRDF are considered apart from a Lambertian target assumption. The surface is always assumed homogeneous. The inputs on viewing and illumination geometry, atmospheric conditions and ground height, are used to estimate the atmospherically corrected reflectance (ρ_{ac}):

$$\rho_{ac}(\theta_s,\theta_v,\phi_s-\phi_v)=\frac{\rho_{ac}'}{1-\rho_{ac}'\cdot s} \tag{1}$$

where s stands for the spherical albedo of the atmosphere, θ_s and θ_v are the sun illumination and viewing zenith angles, and ϕ_s- ϕ_v is the relative azimuth angle. ρ_{ac}' is given by equation 2, where ρ_i^* is the input apparent reflectance, ρ_a is the atmospheric reflectance, T_g is the total two-way gaseous transmittance, and $T(\theta_s)$ and $T(\theta_v)$ are the total scattering transmittances on the downward and upward paths (Vermote et al., 1997b):

$$\rho_{ac}'=\frac{\dfrac{\rho_i^*(\theta_s,\theta_v,\phi_s-\phi_v)}{T_g}-\rho_a(\theta_s,\theta_v,\phi_s-\phi_v)}{T(\theta_s)\cdot T(\theta_v)} \tag{2}$$

The main limitations to the operational use of the 6S code is the difficulty in getting the required atmospheric parameters and the computational time involved in running the code on a pixel-by-pixel basis (Zhao et al. 2000).

3 The atmospheric correction simplified method

The approach used here to atmospherically correct the high spatial resolution images is briefly described in this section. It essentially consists of a slight modification of the method presented in Nunes et al (2004) where a detailed description is made.

3.1 Description of the method

The method performs a simplified atmospheric correction on the remotely sensed Earth's surface reflectance images, using a reduced set of inputs. The sensitivity analysis performed on the 6S RTC (Nunes et al. 2004) supports the assumption of computing the BOA reflectance (ρ_B) for each image pixel as a function of only six variables (equation 3), being the ground horizontal visibility one of the most relevant parameters:

$$\rho_B=\rho_B(\rho_T,\theta_S,\theta_V,\phi_V,h,v) \tag{3}$$

ρ_B is the TOA reflectance, θ_s the sun zenith angle, θ_v the viewing zenith angle, ϕ_v the viewing azimuth angle, h the ground height and v the ground horizontal visibility at 0.550µm. The approach proposed is based on two main assumptions: (1) the effect on BOA reflectance value of varying each variable has reduced influence on the remainder, i.e. that the variables are nearly independent on a first approach; (2) the set of values corresponding to each image pixel may be considered as a slight deviation around a reference set of values. These reference values, *(ρ_T^0, θ_s^0, θ_v^0, ϕ_v^0, h^0, v^0)*, correspond to the most representative scenario for a given location and period of the year. Adequate atmospheric and aerosols' models are set and an appropriate range and variation step increment is established for each variable. The 6S RTC is run in advance, with each variable being varied separately around the reference values. The partial variations induced on the BOA reflectance are evaluated and stored on one-dimensional LUTs. For any set of input values, the BOA reflectance ρ_B' is estimated by adding to the reference value ρ_B^0 all the partially induced variations, using a simple finite differences first order approximation (equation 4).

$$\rho_B{}' = \rho_B(\rho_T,\theta_S,\theta_V,h,v) = \rho_B\left(\rho_T{}^0 + \delta\rho_T,\theta_S{}^0 + \delta\theta_S,\theta_V{}^0 + \delta\theta_V,h^0 + \delta h,v^0 + \delta v\right)$$

$$= \rho_B{}^0 + \Delta\rho_B(\delta\rho_T) + \Delta\rho_B(\delta\theta_S) + \Delta\rho_B(\delta\theta_V) + \Delta\rho_B(\delta\rho_T) + \Delta\rho_B(\delta v) \qquad (4)$$

The partial differences $\Delta\rho_B(x)$, where x stands for the deviation around each reference value, are computed by linear interpolation using the corresponding one-dimensional LUT. The computational implementation of this approach is much easier than using multidimensional LUTs, as the total number of scenarios to simulate is only a few hundreds.

3.2 Performance evaluation - simplified method vs. 6S RTC

The method was previously tested on AVHRR visible and near-infrared channels data (Nunes et al.). The spectral location of the SPOT/HRVIR and ASTER VNIR bands 2 and 3 is similar to AVHRR bands 1 and 2, and a comparable result of the evaluation would most likely be obtained for the sensors. For this performed test, the atmospheric and aerosols models were set to 'mid-latitude summer' and 'continental', respectively (Vermote et al. 1997b). The viewing and illumination conditions were chosen appropriately for the AVHRR sensor and the test area – the continental area of Portugal (latitude 37° N to 42° N; longitude 7° W to 9° 30' W). According to these conditions and based on a set of AVHRR images, one thousand scenarios were generated at random. For that set of scenarios, the BOA reflectance values estimated by the used method (black crosses) are plotted against the 6S direct computation results for AVHRR channel 1 (figure 1). The input TOA reflectance values were also plotted for reference (grey circles).

It is clear from this figure that even a simplified correction is much better than using the uncorrected data. Most of the simulated scenarios fall close to the identity line (black) except for the very high and very low reflectance values, far from reflectance reference value, $\rho_T^0 = 0.15$. It also reveals some difficulties in dealing with low ground horizontal visibility values, caused by the dual behaviour of the estimated BOA reflectance on such circumstances. The overall accuracy in comparison to the 6S RTC was very encouraging with root mean square errors around 1% on both channels and for the whole set of scenarios (Nunes et al. 2004). A greater accuracy is expected for real situations, as occurrence of extreme values for input variables is not as frequent as in the completely random set of scenarios.

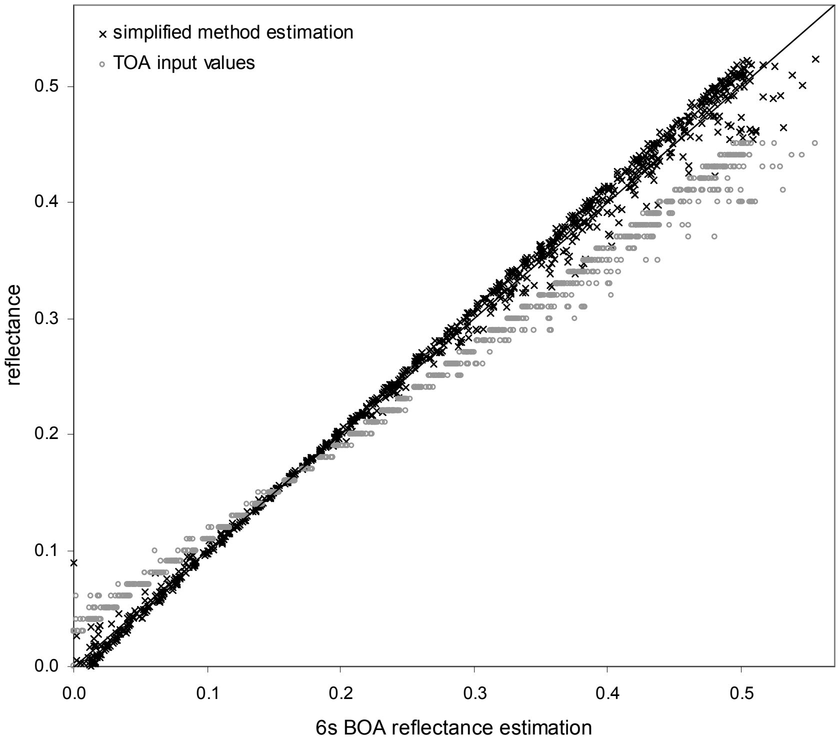

Figure 1. Evaluation of the accuracy of the simplified atmospheric correction method: comparison with 6S RTC direct estimation.

4 Results and discussion

4.1 Application to coastal zone monitoring

The atmospheric correction method described in the previous section was at first designed to be applied mainly over land, where ground horizontal visibility measurements are obtained with reasonable spatial and temporal coverage from Meteorological Offices, airports and aerodromes. For the coastal zone project COSAT (COastal zones monitoring using remote sensing SATellite data), the purpose is to estimate the BOA reflectance over water around the sea breaking zone. The dependence of the water reflectance with the amount of suspended matter is a well-known fact in remote sensing (e.g. Doraxan et al. 2002). In order to have a relationship between TSM and BOA water reflectance, accurate calibration and atmospheric correction of the images has to be made. The latter is with no doubt the most challenging task, particularly due to the very low values of water reflectance.

Two ASTER images (8 and 24Oct.2001) and one SPOT/HRVIR (14Oct.1998) image of the study area were used within this application. The first three bands of each image, in the visible and near-infrared spectral region, have been calibrated to TOA reflectance values and atmospherically corrected using the simplified method. The reference scenarios were established for each image, with the input variables set to the most likely values (Table 1). The atmospheric and aerosol models were set to 'mid-latitude summer' and '90% maritime and 10% continental', respectively.

	ASTER I (08 Oct 01)	ASTER II (24 Oct 01)	HRVIR (14 Oct 98)
θ_s (°)	47.7	53.5	49.9
ϕ_s (°)	167.0	169.0	165.0
v (km)	15 [5;100]	12 [5;100]	10 [5;100]
h (m)	10	10	10
$\rho_{TOA}{}^1$	0.07 [0;0.50]	0.07 [0;0.50]	0.08 [0;0.40]
$\rho_{TOA}{}^2$	0.05 [0;0.60]	0.05 [0;0.60]	0.045 [0;0.40]
$\rho_{TOA}{}^3$	0.03 [0;0.90]	0.03 [0;0.90]	0.03 [0;0.40]

Table 1. Typical scenarios used for generation of LUTs (typical [minimum; maximum])

The visibility is a parameter which is prone to wide variation in both space and time, even for relatively small areas. It is known (e.g. Zieliński and Zieliński, 2002) that aerosol composition and loading is very variable over coastal waters, strongly depending on wind behaviour characteristics (direction, velocity and duration). Right above the breaking zone there is also an extra input of aerosol in the atmosphere due to the amount of water released by the breaking waves. Unless field data is available for the particular location and time desired, such a detailed characterisation is very difficult to obtain. In the present application, the ground horizontal visibility values were taken from meteorological data from the national network of meteorological stations (Instituto de Meteorologia), in which measurements are made every 3 hours. There are other possible sources for the horizontal visibility data, such as the on-line "The Weather Underground, Inc" (www.wunderground.com) which gathers data not only from meteorological offices but also from airports, aerodromes, and other locations. A visibility map for the whole area is generated for the time of image acquisition by temporally and spatially interpolating the available visibility measurements.

4.2 Atmospherically corrected data

4.2.1 The corrected satellite images

For the atmospheric correction of the three satellite images described in section 4.1, the simplified method was applied according to the parameters ranges shown in table 1. Special attention was given to the sea water area, for which the 'typical' values had been chosen. The method performs an atmospheric correction on a pixel-by-pixel basis, and each variable is prone to take different values at different pixels. Due to the small dimension of the target area, some of the parameters (viewing and illumination geometry) present negligible variation within the whole interest zone, and were therefore set to their typical values throughout. The effect of ground height has to be considered in atmospheric corrections over land as it can widely vary even within a small scene. For this application over sea water, the target height was taken as constant and set to the typical value of 10m. The ground horizontal visibility, the most critical parameter and the one more prone to vary on a pixel scale. Unfortunately, for this specific study area, only one station was providing visibility measurements for all of the image dates, and thus the visibility had to be taken as homogeneous in the whole area, although taking different values on different dates (see Table 1). Under these circumstances, the only input variable actually corrected at the pixel scale is the measured TOA reflectance. Figure 2 shows the ASTER I channel 1 image before (left) and after (right) the atmospheric correction. A pseudo colour table was generated with the help of *PCI Geomatics* software (PCI Geomatics 2001) for an enhanced visual interpretation.

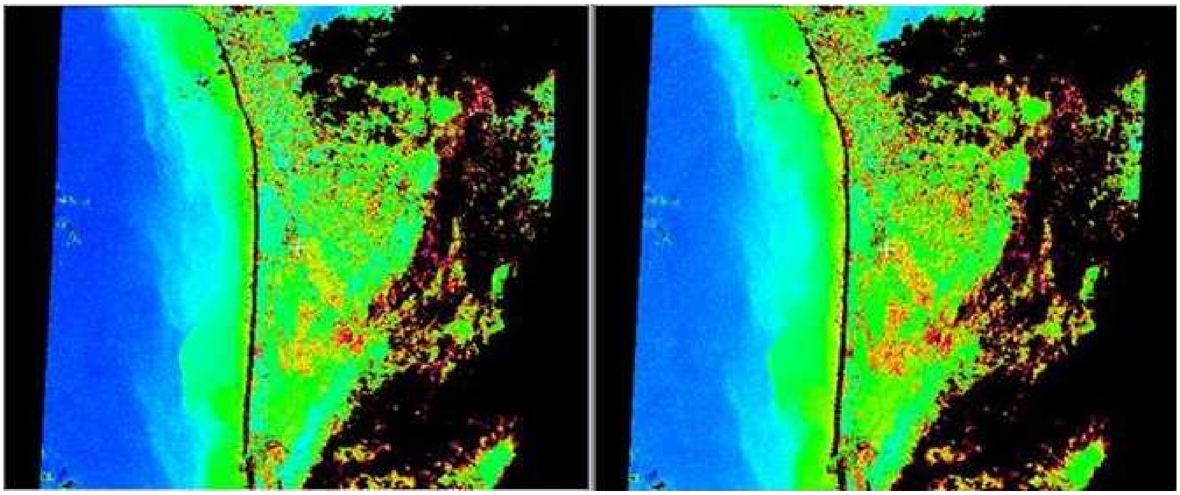

Figure 2. ASTER channel 1 image (08 October 2001) of the study area: TOA (left) and BOA (right) reflectance

As we can see in figure 2, the differences in the TSM patterns between TOA and estimated BOA reflectance images are not very noticeable. There is a difference in the range of values, but this does not affect the distribution patterns. The limited availability of information about the ground horizontal visibility values, which forced this variable to be taken as homogeneous, might be the main cause of this result. Considering that the TOA reflectance was the only variable actually varying within each image, the atmospheric correction method results in a simple linear transformation function between input (TOA) and output (BOA) reflectance values. This would not be the case if the visibility was allowed to vary spatially, as it is expected to happen.

4.2.2 Performance evaluation with ground data

Another evaluation of the atmospheric correction performance was carried out on these images. Figure 2 shows a plot where the range of reflectance values for a number of sand areas identified in the images is represented with atmospheric correction (solid line ellipses) and without atmospheric correction (dashed line ellipses), for both ASTER and HRVIR used bands. Also displayed on the graph is a plot of the average reflectance spectrum of sand, obtained from field surveys at several beaches in the study area. Under these conditions, the method showed to perform reasonably well (especially in the near-infrared region) for medium to high reflectance values.

Although this simplified method had shown a good accuracy when compared to the 6S RTC, its performance over water is rather poor, when compared to ground data. The water reflectance is very low, both in the visible and near-infrared bands. For at-sensor reflectance values in the range 0-6%, most of the recorded signal is due to the effect of the atmosphere. Under low visibility conditions, the 6S RTC seems to overcorrect this effect and as a consequence, the estimated BOA reflectance sometimes takes null or even negative values for coastal water. If this is found to be a drawback of the 6S RTC alone, maybe the use of another RTC would be enough to overcome this limitation. Nevertheless, another improvement of the atmospheric correction method is planned to be carried out in a near future, combining a ‘dark target’ approach (using deep sea water reflectance) and other stable reflectance targets. A new set of field measurements is scheduled for the summer/autumn 2004, which should allow for a better evaluation of the errors associated with the use of sand areas as stable reflectance targets.

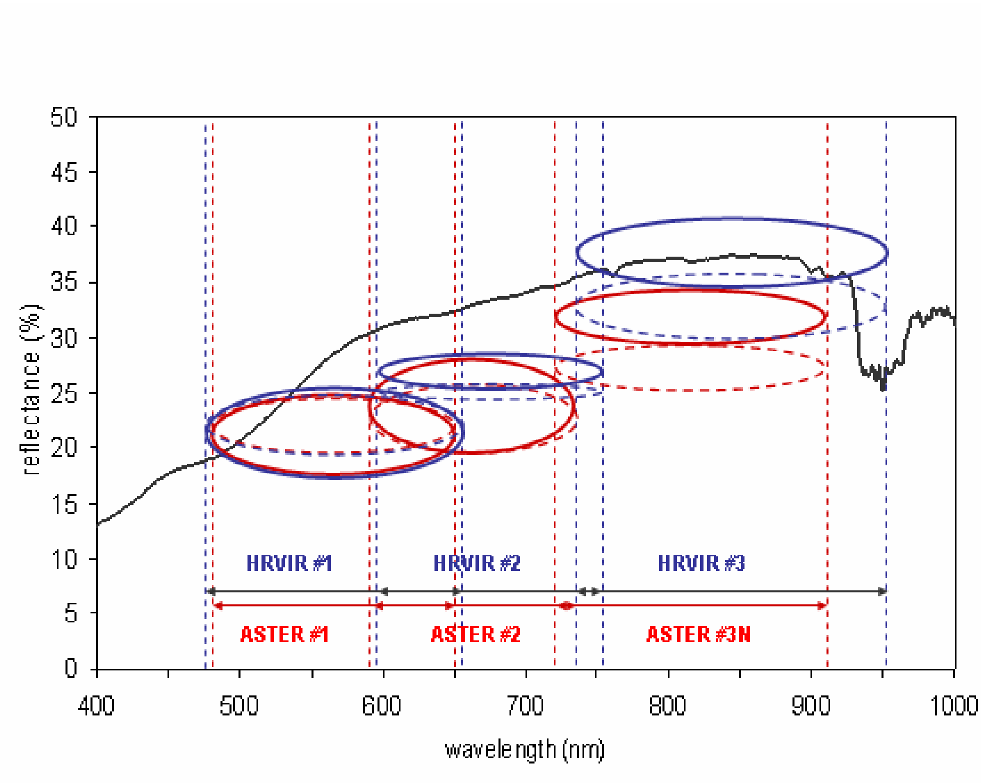

Figure 3. Atmospheric correction evaluation for SPOT (blue) and ASTER VNIR (red) bands.

5 Conclusions

Atmospheric corrections of Earth observing satellite images are not often used due to the high computational effort and the lack of auxiliary data. Some modern high spatial resolution sensors (e.g. ASTER) already provide atmospherically corrected data. Other sensors like Landsat/TM and SPOT/HRV(IR) are a valuable source of present data and, in many cases, of the only historic records. These datasets need to be corrected for most applications.

A simplified pixel-by-pixel atmospheric correction method based on the 6S RTC (Radiative Transfer Code) was applied to SPOT/HRVIR and ASTER satellite images over sea coastal waters. These atmospherically corrected reflectance images are used to estimate the amount of TSM (Total Suspended Matter). The very low reflectance values of the sea water in the visible and near infrared spectral zones make atmospheric corrections a challenging task. The method performed well when compared to the 6S RTC (rmse around 1%) but not so well against ground data. The very low reflectances still pose some problems as they are sometimes corrected to negative values. When comparing the atmospherically corrected and non-corrected reflectance images, a difference in the range of reflectance values is clear. Noticeable differences in the TSM patterns distribution are not detected, but that might be caused by the use of a single ground horizontal visibility value for the whole image.

Further improvements of the simplified method are currently being developed. The use of ground reflectance data of known stable targets (e.g. deep sea water, sea sand areas, etc) is to be used together with this approach. The use of 'ASTER surface reflectance' data for comparison with surface reflectance estimated by the simplified method might allow for its further calibration and more effective performance on images from other satellite sensors.

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