AN INVERSE RADIATIVE TRANSFER MODEL TO EXTRACT GROUND SPECTRAL REFLECTANCE OF URBAN AREAS

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ABSTRACT

Automatic mapping of urban materials from remotely sensed radiance images remains difficult because of the complex phenomena induced by relief. Indeed, shadows and environment effects disrupt the radiance incoming the sensor. The measured radiance depends on the illumination conditions of the observed area.

This study proposes a physical model able to solve the radiative transfer inversion problem in urban areas, in the reflective domain (0.4 µm – 2.5 µm), from high spatial and spectral resolution images. This new approach takes into account the relief, the spatial heterogeneity of the scene and atmospheric effects, in order to extract rigorously the ground surface reflectance. The method consists in modelling separately the irradiance and radiance components at ground and sensor levels.

The validity of the various assumptions introduced in this model is checked through comparisons with Amartis, which is considered as a reference direct radiative transfer code. The results obtained over different typical urban scene and for various wavelengths show an absolute error of less than 0.01 on the retrieved reflectance after the inversion process.

A field campaign was also carried out in Toulouse (France) in order to validate the model in real conditions. Measurements were carried out using two airborne Pelican sensors consisting in 8 high resolution cameras. The main results are that the estimated reflectances from the same material in sunny and shadowed areas exhibiting no bias. It means in particular that the topographic and environment effects are accurately corrected. Furthers, the main close error comes from the misregistration between the DEM and the radiometric images.

INTRODUCTION

Recent studies estimate that more than 75% of the world population are living in urban areas. Many applications required a better understanding of this environment to analyse its development. With the advent of high spatial resolution sensors in the visible and near infrared domain [0.4 µm – 2.5 µm], it becomes possible to obtain precise information from airborne or satellite images.

Due to their highly structured geometry, an important part of urban areas exhibits shadows. Thus, urban acquisitions will depend on the illuminations conditions. This drawback must be overcome to improve applications as mapping or urban change detection, which often use images from different years or different sensors. As the urban environment makes it difficult to classify automatically urban materials from airborne radiance measurements, preprocessing algorithms are usually used to extract ground surface intrinsic properties like reflectance that is independent of the irradiance conditions.

Currently, different methods are used to solve the inverse transfer radiative problems (i.e. retrieving ground reflectance from radiance images). Most of these codes consider a flat and homogeneous landscape and a lambertian assumption, e.g., ATREM (i), ACORN (ii). Improvements have been carried out in FLAASH and COCHISE as they consider a heterogeneous background. Nevertheless, these codes are not able to deal with urban areas where the relief plays very important part in the remotely sensed features. Two models currently take into account the ground topography: ATCOR4 (iii) and SIERRA (iv), but these codes are not adapted to the very uneven structure of urban areas, notably in shadows, where the earth-atmosphere coupling phenomena are still roughly modelled.

The need for a radiative transfer model that is able to understand and model the signal over urban areas led us to develop the method we report here. This method consists in modelling separately the irradiance and radiance components at ground and sensor level by use of models derived principally from improved versions of the usual spatially resolved approaches. Each component takes into account the relief, ground heterogeneity and atmospheric corrections.

First, in order to check the validity of the different assumptions made, an end-to-end method is applied using the reference radiative transfer model Amartis (v), performed over a typical urban scene. Then, to complete this theoretical validation, a field campaign is carried out to validate our model on real images and first results are presented.

RADIATIVE TRANSFER MODELLING OVER URBAN AREAS

Considering an airborne or satellite sensor observing an urban scene in the visible and near infrared domain [0.4 µm – 2.5 µm] and i a pixel of the sensor image, the total radiance received by this sensor can be written as the sum of three main contributors (Figure 1) :

$$R_{sensor}(i) = R_{diffuse}(i) + R_{atmospheric}(i) + R_{direct}(i) \quad (1)$$

The first component corresponds to scattered photons coming from the target neighbouring ($R_{diffuse}$). $R_{atmospheric}$ describes photons coming to the sensor without reaching the surface.

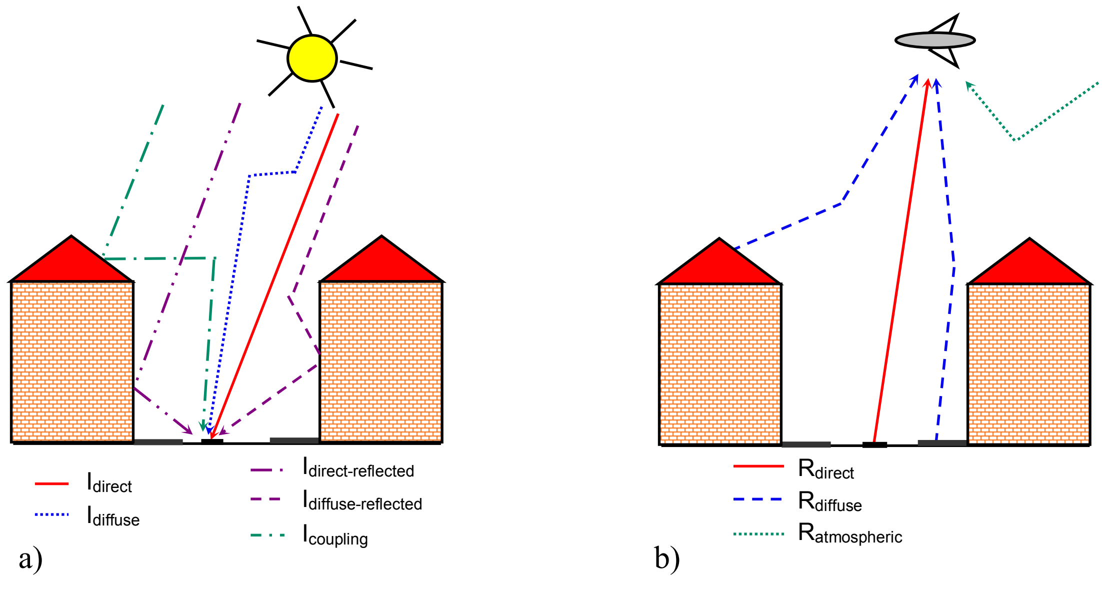


Figure 1: Irradiance components at ground level (a) and radiance components at sensor level (b).

R_{direct} is the upwelling radiance directly transmitted from the ground to the sensor. This component plays an important role as it brings the searched reflectance:

$$R_{direct}(i) = (I_{direct}(P) + I_{diffuse}(P) + I_{reflected}(P) + I_{coupling}(P))\frac{\rho}{\pi}t^{\uparrow} \quad (2)$$

Where P is a ground point and ρ its reflectance. I_{direct}, $I_{diffuse}$, $I_{reflected}$ and $I_{coupling}$ are the different irradiance components incident to the ground according to their type of path (Figure 1).

Using equation 1 and 2, we can extract an analytical expression of the reflectance using a lambertian hypothesis:

$$\rho = \frac{\pi(R_{sensor} - R_{diffuse} - R_{atmospherique})}{T^{\uparrow}(I_{direct} + I_{diffuse} + I_{reflected} + I_{coupling})} \quad (3)$$

To solve this equation, our method consists in estimate each component of equation 2.

The direct irradiance, I_{direct}, which corresponds to photons coming directly from the sun, is generally the dominant one. Its analytical expression depends on the zenith solar angle θ_s, on the slope of the ground and on a binary function (*bool*), set to zero if the point P at ground level is in the shadow and set to one otherwise. Its expression is then:

$$I_{direct}(P) = E_{TOA} \cdot T_g^{\downarrow}(P,\theta s) \cdot \left\langle \vec{N}(P) \cdot \vec{n}_s \right\rangle \cdot e^{-\frac{\tau^{\downarrow}(P)}{\cos(\theta s)}} \cdot bool(P,\theta_s,\varphi_s) \quad (4)$$

Where E_{TOA} is the top of atmosphere solar irradiance, N(P) is a unit vector orthogonal to the slope of the ground model at P, n_s is a unit vector pointed toward the sun, T_g the gaseous transmission and $\tau(P)$ is the total atmospheric optical thickness of the vertical path above P. The brackets indicate a vector dot product.

The second irradiance component, $I_{diffuse}$, models the photons scattered by the atmosphere to the ground. Its analytical expression is obtained by integrating downwelling sky radiances over the solid angle of view of the sky of point P, Ω_{sky}. These radiances are calculated in our model by 6S (vi).

$$I_{diffus}(P) = T_g^{\downarrow}(P,\theta s) \iint_{\Omega sky} L_{sky}^{d}(\theta,\varphi)\cos\theta d\omega \quad (5)$$

The three last components correspond to irradiances depending of the environment. $I_{direct\text{-}reflected}$ and $I_{diffuse\text{-}reflected}$ (Eq. 3) are resulting from reflections of the previous components (I_{direct} and $I_{diffuse}$) on neighbouring pixels.

$$I_{direct\text{-}reflected}(P) = \iint_{\Omega_{sky}} I_{direct}(M_{d\omega}) \frac{\rho(M_{d\omega})}{\pi} \left\langle \vec{N}(P).\vec{n}_{M_{d\omega}P} \right\rangle T_g(M_{d\omega},P) e^{-\tau(M_{d\omega},P)} d\omega$$

$$I_{diffuse\text{-}reflected}(P) = \iint_{\Omega_{sky}} I_{diffuse}(M_{d\omega}) \frac{\rho(M_{d\omega})}{\pi} \left\langle \vec{N}(P).\vec{n}_{M_{d\omega}P} \right\rangle T_g(M_{d\omega},P) e^{-\tau(M_{d\omega},P)} d\omega \quad (6)$$

Where $\rho(M)$ is the reflectance of the neighbouring relief at point M.

In urban structures, narrow roads generate multiple reflections that become significant in shadows. To minimize approximations, our model considers both simple and double reflections. The double reflected irradiance corresponds to reflections of $I_{direct\text{-}reflected}$ and $I_{diffuse\text{-}reflected}$. As we can see on equation (6), the expression of these components depends on the environment and so on the searched reflectance. To solve this problem, an initialisation of the environment reflectances is necessary to compile these equations. Then, an iterative process is used

The last irradiance component is the earth-atmosphere coupling component $I_{coupling}$. It comes from multiples reflections and scattering between ground and atmosphere. An analytical expression was proposed by Tanré (vii) in the case of flat and homogeneous landscapes. Miesch (viii) carried out that this analytical solution is no more valid for a rugged, strongly heterogeneous scene like urban scene and propose a Monte Carlo approach. The need for a fast computational model led us to search an analytical solution adapted for urban areas properties. The proposed expression consists in calculating the earth-atmosphere coupling irradiance above the relief, using Tanré's expression and then, weighting the value for each point of the relief according to its solid angle of view of the sky:

$$I_{coupling}(P) = \frac{\rho_{equivalent} s}{1-\rho_{equivalent} s}(I_{direct\_flatground} + I_{diffuse\_flatground}) \iint_{\Omega_{sky}(P)} \frac{\cos(\theta_{sky})d\omega}{\pi} \quad (7)$$

The equivalent reflectance of the scene is derived from the ground heterogeneity by the following expression:

$$\rho_{equivalent} = \frac{\iint_{\Re} \rho(P)(E_{direct}(P) + E_{diffus}(P) + E_{reflected}(P))\Omega_{sky}(P)dS}{\iint_{\Re} (E_{direct}(P) + E_{diffus}(P) + E_{reflected}(P))\Omega_{sky}(P)dS} \quad (8)$$

As the reflected irradiances, the calculation of this component requires the knowledge of the reflectance of the environment, which should be initialised (similarly to the multiple reflection components).

At this point, we modelled all the irradiance components. The last components to describe are the diffuse radiance and the atmospheric one.

The atmospheric radiance depends on the distance between the relief and the sensor and on the field of view of the sensor: the more atmosphere there is and the more important this component will be. This term is calculated in our model with 6S using an averaged height above the urban scene.

The last component is the diffuse radiance. This component depends on the reflectance of the environment of the target. In order to determine it, the Dark Dense Vegetation method (ix) is applied. The dark pixel that is used in this algorithm often corresponds to vegetation or water which presents low reflectance respectively in the red and the near infrared. Concerning the urban areas, it is quite difficult to find vegetation or water. Thus, we have adapted this solution to tar materials. Their reflectance averaged 0.06 over the whole range studied. Choosing a tar pixel in a shadowing area reduces the error that we could do on this reflectance (Eq. 9). The evaluation of the diffuse radiance is thus more accurate.

$$R_{diffuse} = R_{sensor} - R_{atm} - (I_{direct} + I_{diffuse} + I_{coupling} + I_{reflected})\frac{\rho_{dark\_pixel}}{\pi} T_{dir}^{\uparrow} \quad (9)$$

THEORETICAL VALIDATION BY COMPARISON WITH A REFERENCE MODEL

In this part, the assumptions used in our model are validated. Four input data are available to solve this inverse problem: illuminations conditions (solar incidence and viewing angles), atmospheric parameters (aerosol type and visibility), digital vector models in three dimensions of the scene, and calibrated radiance images of the scene.

Our model has been compared with the Amartis model, developed by Onéra (viii). This direct model was developed to deal with ground heterogeneity and relief in the visible and near infrared spectral domain. The comparison method is based on an end-to-end procedure. In a first step, after having described the landscape in terms of geometry and optical properties, we used the Amartis model to compute a radiance image at sensor level over the scene. Then, the resulting image is processed with our inverse code to extract estimated optical properties. A comparison is then conducted between the input and the estimated optical properties.

Comparisons have been made for various atmospheric conditions, over multiple urban relieves. The results showed in this article have been obtained on a typical urban profile, described on Figure 2. In this scenario, the chosen atmosphere corresponds to the midlatitude summer model, with continental aerosols and a visibility of 23 km. The solar zenith angle is 31° and the sensor is set at 2250 m high and is nadir-viewing.

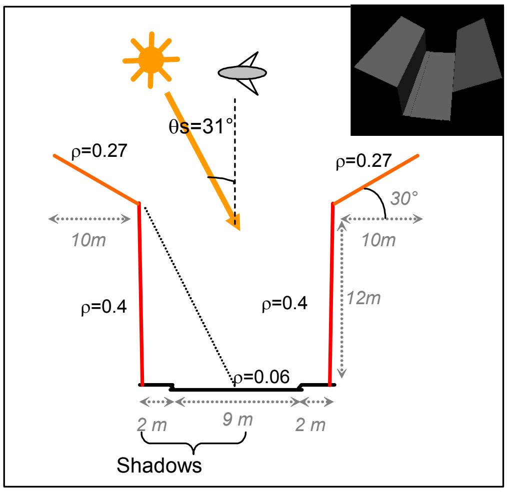


Figure 2: Typical urban profile used for the theoretical validation.

Simulations have been carried out at 450 nm, 650 nm, 850 nm and 1600 nm in order to cover the whole spectral visible and near infrared domain.

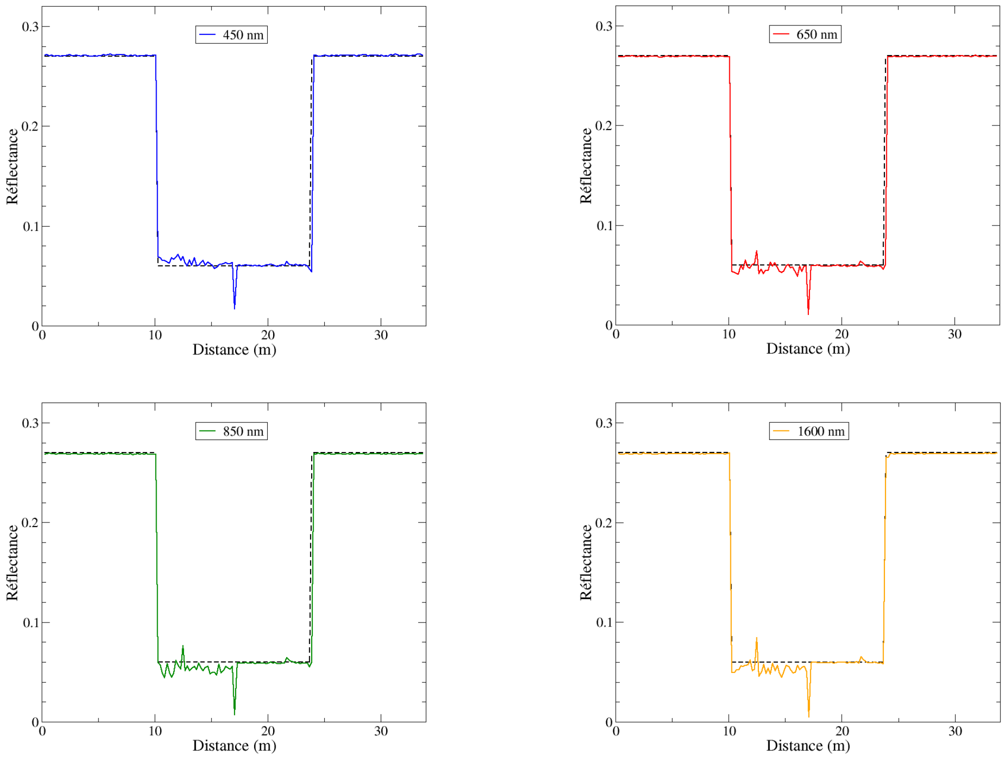


Figure 3: Reflectance profiles obtained after inversion from the simulated Amartis radiance images. a) 450 nm, b) 650 nm, c) 850 nm, d) 1600 nm. The black dashed line represents reference reflectances.

On Figure 4, reflectance profiles obtained after inversion show a very good agreement with the reference, the maximum absolute error being less than 0.01. The peak located at 17 m delimits shadowed and sunny areas. It is due to mixed pixels (shadowed and irradiated) at the sensor level and could be removed easily in the implementation. This result demonstrates the relevancy of the analytical modelling used in our model. There is a good continuity of the reflectance on the ground for shadowed and sunny pixels despite of the low ground irradiance level. Thus, the corrections of the environment effects (diffuse, reflected and coupling components) seem to be appropriate.

EXPERIMENTAL VALIDATION

An experimental validation campaign of this model took place in Toulouse in April 2004, including airborne acquisitions at high spatial and spectral resolutions simultaneously with ground truth measurements within the same resolution. The airborne acquisitions were performed using two high spatial resolution systems (PELICAN) (x) composed of four cameras each. The flight altitude was 2250 m and the spatial resolution at ground level 20 cm. The eight narrow filters associated to the cameras were located in the visible and near infrared spectral domain from 420 nm to 917 nm.

The digital vector model of the scene (Figure 4) was provided by the Institut Géographique National from stereoscopic images of Toulouse acquired in December 2003.

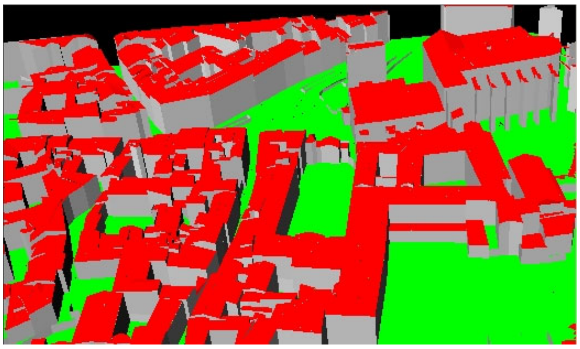
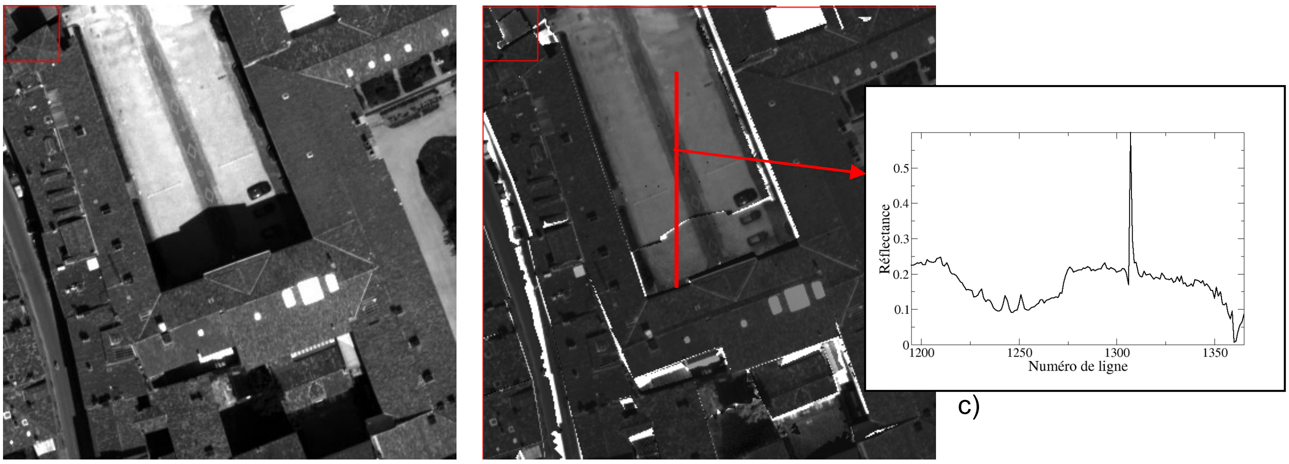


Figure 4: Digital vector model of the prefecture of Toulouse

The aerosols are supposed to be of urban type. Their abundance has been evaluated during the experiment using the Bouguer-Lambert law by measuring direct irradiance during the experiment. The visibility associated to this dataset is 37 km.

Figure 5 illustrates the results produced by the inverse model on the prefecture area in Toulouse. We can see that details which were hidden in shadowed areas like cars appear in the reflectance image. The most important result is that we obtained the same reflectance for ground materials located in shadows and sunny areas (Figure 5, c)). It means that the environment effects are correctly modelled.



a) b) c)

Figure 5: a) Radiance image at 485 nm, b) Reflectance image obtained after inversion at 485 nm c) Reflectance profile along the red line.

White areas in the reflectance image correspond to geometric errors in the digital vector model. The quality of the reflectance image depends entirely of the quality of the vector model of the scene.

CONCLUSIONS

In this work, an inverse radiative transfer model operating in the visible and near infrared is presented. The objective of the study was to develop a code able to deal with urban areas. It takes into account atmospheric corrections and environment effects in order to retrieve ground reflectance from radiance images. To solve the inverse problem, irradiance and radiance components are modelled separately. The effects of the various assumptions made were checked for various atmospheric conditions and relieves. A comparison with the reference model Amartis allows us to validate the model over a typical urban profile. Results show that absolute errors obtained on reflectance profiles is less than 0.01 whatever the wavelength between 450 nm and 1600 nm.

Also, a field campaign was carried out in Toulouse using two PELICAN systems, in order to make an experimental validation of the model. Results demonstrate that the physical modelling is well adapted to urban areas. Shadows are well corrected and there is no bias between reflectances in shadowed and sunny areas for the same materials.

The next step of this work will be to confirm experimental results with ground truth measurements and then to apply usual classification algorithms on the images. A comparison between results obtained respectively with radiance and reflectance images would allow us to quantify the improvement provided by the inversion method.

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