Remote Sensing of Environment 157 (2015) 85–95

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Sensor independent adjacency correction algorithm for coastal and inland water systems

Viacheslav Kiselev [a,*], Barbara Bulgarelli [b], Thomas Heege [a]

[a] EOMAP GmbH & Co. KG, Seefeld Castle, Schlosshof 4, 82229 Seefeld, Germany
[b] European Commission — Joint Research Centre (JRC), 21027 Ispra, VA, Italy

ARTICLE INFO

Article history:
Received 29 November 2013
Received in revised form 9 July 2014
Accepted 18 July 2014
Available online 18 August 2014

Keywords:
Satellite image
Adjacency correction
Point spread function
Searchlight problem

ABSTRACT

The presented adjacency correction algorithm is based on the use of the point spread function (PSF) which allows calculating the contribution of reflections from the nearby pixels to the apparent radiance of the target. The analytical expression of the PSF for an arbitrary stratified atmosphere is obtained in the approximation of primary scattering, whereas the full equation of radiative transfer is used for the estimation of the radiance reflected from the surface. The algorithm is sensor independent and can be applied for processing images of water basins with arbitrary shape of the shore line and under different geometries of observation. The program using this algorithm is included in Modular Inversion Program — MIP (Heege et al., 2014) for processing of satellite images on a routine basis. Examples of processing results are presented in the paper.

1. Introduction

Adjacency effect is one of the types of distortion of satellite images of the Earth's surface which results from the presence of a scattering atmosphere between the surface and the sensor. In the absence of the atmosphere, the radiance detected by a sensor observing a target element on the surface would just originate from the photons reflected by the target element itself. In the presence of a scattering atmosphere, two additional contributions appear: the radiance owing to photons which interacted only with the atmospheric optically active components (the so called atmospheric radiance), and the radiance owing to photons which, after having interacted with the surface surrounding the target element, are further scattered by the atmosphere toward the sensor. Conventional methods for the processing of satellite and airborne data (see e.g. Doerffer & Schiller, 2007) mostly take the latter photons into account assuming a horizontally homogeneous surface with the same reflectance properties as the target element. In the regions where sharp contrasts of reflectance exist, the real radiances may significantly diverge from those corresponding to this assumption, and their difference is called the adjacency effect. The presence of this effect, i.e., the absence of correspondence between real radiances and those resulting from the assumption of a homogeneous surface, evidently distort the signal from the target, and the accuracy of the retrieval of target characteristics correspondingly decreases.

One of the possible operational approaches to take the adjacency effect into account is to assume that the reflectance of the surrounding area is an average reflectance of some environment of the target. This approach, however, uses formulae, which are strictly valid only for a horizontally homogeneous underlying surface. Hence it is based on the assumption that it is possible to select the averaging scale for the surface reflectance in such a way that its sliding average in the considered area is not significantly varying. For that reason it gives good results for purely land scenes (Richter, 1996; Vermote & Vermeulen, 1999), but is hardly applicable in other cases, like for the costal zones, where the sliding average of surface reflectance for any averaging scale varies from typical land to typical water value.

For the adjacency correction of water scenes more perspective are the methods based on the point spread function (PSF), which describes the dispersion of light from a point source when transferred through the scattering medium. The use of this function allows to directly calculate the contribution of the reflections from the surrounding surface elements to the signal at the sensor. The inherent difficulty of this approach is that the estimation of the PSF requires the solution of the three-dimensional radiative transfer equation (RTE) that can be accurately done only numerically and which requires a lot of computer time. For operational purposes it is natural to use a simplified approach, and in this paper the solution of the RTE in the approximation of primary scattering is used. The PSF for a Lambertian surface is obtained as an integral of the solution of the searchlight problem, i.e., of the transfer of light emitted by a monodirectional point source. Although the primary scattering approximation for the searchlight problem was considered beginning from the middle of the last century (Dunn & Siewert, 1985; Rosenberg, 1960), the solutions were restricted to a vertically homogeneous atmosphere. The present study extends the solution of the searchlight problem to the case of an atmosphere with arbitrary stratification.

* Corresponding author.

http://dx.doi.org/10.1016/j.rse.2014.07.025

The previous methods for the adjacency correction of satellite images of water scenes were oriented on specific sensors (Guanter et al., 2010; Reinersman & Carder, 1995; Santer & Zagolski, 2009), required the presence of sensor channels in a specific spectral region (Sterckx, Knaeps, & Ruddick, 2011) or although they can be adapted to various sensors were not intended to be operationally used (Brando & Dekker, 2003; Brando et al., 2009). The proposed methodology does not impose any restriction on sensor characteristics and specifications; additionally, it allows a quantification of the adjacency effects for any angle of observation, taking into account the actual coastal morphology and, in principle, also the sea surface anisotropy. It can be hence applied for the operational processing of satellite images obtained by different multi- and hyperspectral sensors for a continental coverage.

2. The PSF for a Lambertian surface

The 3-dimensional equation of radiative transfer for a vertically stratified medium can be written as:

$$\left[\eta\frac{\partial}{\partial z}+\sqrt{1-\eta^2}\left(\vec{n},\vec{\nabla}\right)\right]\tilde{L}\left(z,\vec{r};\eta,\vec{n}\right) = -\sigma(z)\tilde{L}\left(z,\vec{r};\eta,\vec{n}\right)+\frac{\kappa(z)}{4\pi}\int x(\gamma,z)\tilde{L}\left(z,\vec{r};\eta',\vec{n}'\right)d\eta' d\vec{n}', \quad (1)$$

where z and $\vec{r}=(x,y)$ are the Cartesian coordinates; $\eta=\cos\theta$, $\vec{n}=(\cos\phi,\ \sin\phi)$, and θ and φ are the polar coordinates; $\tilde{L}\left(z,\vec{r};\eta,\vec{n}\right)$ is the radiance in the point $\left(z,\vec{r}\right)$ propagated in the direction $\left(\theta,\vec{n}\right)$; $\sigma(z)$ and $\kappa(z)$ are the extinction and scattering coefficients, respectively; $x(\gamma)$ is the phase function, γ is the scattering angle; and $\vec{\nabla}$ is the gradient operator:

$$\vec{\nabla}=\vec{i}\frac{\partial}{\partial x}+\vec{j}\frac{\partial}{\partial y}, \quad (2)$$

with $\vec{i}$ and $\vec{j}$ being the unit vectors in the directions of the x- and y-axis, respectively.

For the monodirectional point source on the surface emitting radiation in the direction (η_0,φ_0) the lower boundary condition is:

$$\tilde{L}\left(0,\vec{r};\eta,\vec{n}\right)=S\delta(x,y)\delta(\eta-\eta_0,\varphi-\varphi_0). \quad (3)$$

For simplicity the source is assumed to be located in the coordinate origin. The δ-functions are normalized for convenience in the following way:

$$\frac{1}{4\pi}\int\delta(\eta-\eta_0,\varphi-\varphi_0)d\eta d\varphi=1 \qquad \int\delta(x,y)dxdy=1 \quad (4)$$

and the integration in Eq. (4) is performed over the whole space where the variables are defined. With this normalization the source flux through the surface normal to the direction of the pencil of radiation is $4\pi S$.

The solution of the above problem is (see Appendix A):

$$L\left(z,\vec{r};\eta,\vec{n}\right)=\frac{S}{R}\eta_0\kappa(z^*)x(\gamma_0,z^*)\exp\left[-\frac{1}{\eta_0}\int_0^{z^*}\sigma(z')dz'-\frac{1}{\eta}\int_{z^*}^{z}\sigma(z')dz'\right]\delta\left(\vec{n},\left[\vec{n}_p\times\vec{n}_0\right]\right) \quad (5)$$

for $0\le z^*\le z$ and 0 in the other case. In Eq. (5) unit vectors $\vec{n}$, $\vec{n}_0$ and $\vec{n}_p$ identify the directions of the scattered radiation, of the incident beam and to the observation point, respectively, and

$$R=\sqrt{x^2+y^2+z^2}, \quad (6)$$

so that

$$z=R\eta_p=R\cos\theta_p \qquad r=R\sqrt{1-\eta_p^2} \quad (7)$$

and

$$z^*=R\eta_0\frac{\left(\left[\vec{k}\times\left[\vec{n}\times\vec{n}_p\right]\right],\left[\vec{k}\times\left[\vec{n}\times\vec{n}_0\right]\right]\right)}{\left(\left[\vec{k}\times\left[\vec{n}\times\vec{n}_0\right]\right],\left[\vec{k}\times\left[\vec{n}\times\vec{n}_0\right]\right]\right)}. \quad (8)$$

In Eq. (8) $\vec{k}$ is the unit vector along the z axis and the square brackets denote the vector product; γ_0 is the angle between the radiation emitted by the source and the radiation in the measurement point.

In order to clarify the physical meaning of z^* the unit vector $\vec{n}_r$ normal to the plane defined by vectors $\vec{n}$ and $\vec{n}_0$ (the scattering plane) is introduced. Since the expression in Eq. (5) is different from zero only if $\vec{n}_p$ lies in the same plane, it is possible to write:

$$z^*=R\eta_0\frac{\sin\gamma_0\sin\xi\left(\left[\vec{k}\times\vec{n}_r\right]\bullet\left[\vec{k}\times\vec{n}_r\right]\right)}{\sin^2\gamma_0\left(\left[\vec{k}\times\vec{n}_r\right]\bullet\left[\vec{k}\times\vec{n}_r\right]\right)}=R\eta_0\frac{\sin\xi}{\sin\gamma_0}, \quad (9)$$

where γ_0 is the angle between vectors $\vec{n}$ and $\vec{n}_0$ (i.e., the scattering angle), and ξ is the angle between vectors $\vec{n}$ and $\vec{n}_p$ (see Fig. 1). As can be seen from Fig. 1, $R\sin\xi/\sin\gamma_0$ is the distance from the coordinate origin to the point of scattering. Further multiplying this distance by η_0 gives z^*, which evidently is the z-coordinate of the point of scattering.

In order to obtain the PSF for any type of surface it is necessary to make a convolution of Eq. (5) with the corresponding bidirectional reflectance distribution function. This means that for the simplest surface type, namely a Lambertian reflecting surface, it is simply necessary to integrate Eq. (5) in η_0 and φ_0 over the upper hemisphere. This leads to the formal expression:

$$\bar{L}(z,r;\eta,\varphi)=S\int_0^1 d\eta_0\int_0^{2\pi}d\varphi_0\frac{\eta_0}{R}\kappa(z^*)x(\gamma_0,z^*)\exp\left[-\frac{1}{\eta_0}\int_0^{z^*}\sigma(z')dz'-\frac{1}{\eta}\int_{z^*}^{z}\sigma(z')dz'\right]\delta\left(\vec{n},\left[\vec{n}_p\times\vec{n}_0\right]\right). \quad (10)$$

In view to further apply Eq. (10) for the estimation of the adjacency effects a new coordinate system is introduced. The original coordinate system (x,y) on the horizontal plane is substituted by the polar coordinate system with the pole in the target point (point M, see Fig. 2), and the azimuth is measured clockwise from the direction opposite to the projection of the vector $\vec{n}$ on the horizontal plane.

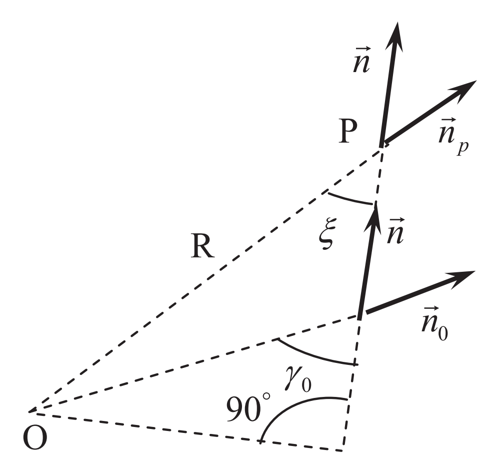

Fig. 1. Vectors in the scattering plane. O is the origin of the coordinate system, where the source is located; P is the point of measurement.