ABSTRACT

Sentinel-4 will offer unprecedented possibilities to monitor the daily cycle of trace gases over Europe provided the surface reflectance field is well characterised. This paper discusses possible ways to define a surface LER when the AF BRF is known.

1. INTRODUCTION

The determination of trace gases such as NO\textsubscript{2}, HCHO or SO\textsubscript{2} daily cycle from Sentinel-4 (S4) observations [1] requires an accurate knowledge of the surface reflectance properties as Bidirectional Reflectance Factor (BRF) magnitude undergoing important variations during the course of the day over land. These variations result from changing illumination conditions at each S4 acquisition cycle. The shape of these daily variations, due to the anisotropy of the surface reflectance, depends both on surface structural and optical properties, and illumination conditions that are controlled by the sun position and the amount of sky radiation around this position. The intensity of the sky radiation is determined, among other things, by the aerosol concentration in the atmosphere. As the aerosol optical thickness varies with the wavelength, it is therefore expected that the way sky radiation shapes the surface BRF is also wavelength-dependent.

To correctly account for these scattering feedback processes between the surface and the atmosphere, it is necessary to perform the retrieval using coupled Radiative Transfer Model (RTM), i.e., where surface reflectance is radiatively coupled with atmospheric scattering. Unfortunately, such coupling is pretty CPU intensive in case of anisotropy surface reflectance. Several approximation methods have been used so far for the retrieval of atmosphere chemical composition to circumvent this issue. The most widely used approximation assumes that surface BRF field can be represented by a Lambertian Equivalent Reflectance (LER) one. Such assumption greatly reduces the amount of computer time that should be dedicated to calculate this coupling, a criteria particularly relevant for the near real-time processing of S4 data. To further reduce the computer time, solutions of the Radiative Transfer Equation (RTE) are pre-computed in Look-Up Tables (LUTs). The LER assumption considerably reduces the number of size of these LUTs.

However, there is no unique way to estimate the LER when surface BRF is known. The objective of this paper is to discuss different possible ways to define a LER surface and the actual surface BRF field is known.

Section (2) defines theoretical concepts of surface reflectance. Section (3) explains through illustrative examples the way sky radiation shapes surface BRF as a function of the wavelength and scattering optical thickness. These results are used to demonstrate the impact of LER - surface BRF relationships in the various S4 spectral regions.

2. REPRESENTING THE SURFACE REFLECTANCE ANISOTROPY

Several attempts have been performed so far to document the impacts of accounting for surface reflectance anisotropy in satellite retrievals of tropospheric nitrogen dioxide NO\textsubscript{2} [2,3]. The retrieval of this molecule concentration is particularly demanding in terms of surface BRF accuracy. Reference [2] states that surface BRF represents an intrinsic property of the surface and describes the scattering of a parallel beam of incident light to a reflected direction in the hemisphere. Such definition of an intrinsic property is true in an atmosphere-free (AF) case but does not hold when a scattering atmosphere lays on top of the surface. In that case, the incident radiation is not composed anymore of parallel beam. In this paper, we therefore clearly discriminate the AF surface BRF and the actual bottom-of-atmosphere (BOA) BRF field. This latter quantity denotes the surface reflectance field observed below a scattering atmosphere.

Surface reflectance anisotropy essentially results from the size of the scattering elements, e.g., plant leaves, which are much larger than the wavelength, casting
thereby shadows from one scattering element on the other ones. The shape and magnitude of this anisotropy depends on the structural properties of the surface such as the Leaf Area Index (LAI) and their optical properties such as the reflectance and transmittance of plant leaves. Considering a single illumination and viewing direction, the intensity of the reflectance is indeed an intrinsic property of the surface. Various models have been developed to simulate the AF BRF field \( r(\Omega_s(t),\Omega_v;\mathbf{p}) \) corresponding to a uncollided illumination direction \( \Omega_s(t) \) and viewing one \( \Omega_v \) as a function of a set of parameters \( \mathbf{p} \) [e.g., 4,5].

Figure 1: Simulated bottom-of-atmosphere (red line) BRF at 320 nm over Paris for two aerosol optical thicknesses given at 550nm: 0.1 (dashed line) and 1.0 (solid line). The surface BRF with no atmospheric coupling is shown with the green line. The sun angles are for 21 June.

The green line on Fig. 1 shows typical daily variations of the AF surface BRF field as seen by S4 at 320nm for a pixel located over Paris. In this example, the surface model parameters are kept constant during the course of the day. In other words, the intrinsic radiative properties of the surface characterized by the parameters of the surface BRF model, are kept constant. The observed BRF field variations are due to changing illumination conditions during the course of day. In this AF case, reflectance anisotropy essentially results by shadowing effects. Morning and afternoon reflectances are pretty low as a result of high sun zenith angles casting shadows on important parts of the pixel. As the sun zenith angle decreases, so does the ratio shadowed areas with respect to the lit ones, resulting in an overall increase of the surface reflectance.

In practice, it is not possible to observe in the field AF surface BRF as the incoming incident radiations has interacted with the atmosphere and does not form a parallel beam anymore. The solid and dashed red lines on Fig. 1 show the BOA BRF field corresponding to two different aerosol optical thicknesses. As can be seen from this example, the surface BRF field is not anymore only an intrinsic property of the surface but also depend on the illumination conditions, i.e., the ratio between the direct and diffuse incident radiation. In other words, in addition to surface structural and optical properties, the shape of the BRF is also determined by the amount of sky radiation.

Sky radiation, resulting from light scattering by atmospheric molecules and particles, tends to smooth the magnitude of the surface BRF as it lights the shaded areas, reducing thereby the contrast between lit and shaded areas. Sky radiation reduces thus the intensity of surface reflectance anisotropy effects translating in the example shown on Fig. 1 (red lines) in larger reflectance values at the bottom of the atmosphere (BOA) in the morning and in the afternoon and smaller ones around noon.

As can be seen from this simple example, as the surface BRF field also depends on the sky radiation, there is no simple way to define the LER once the surface intrinsic AF BRF field is fully characterised.

3. RADIATIVE COUPLING BETWEEN THE SURFACE REFLECTANCE AND ATMOSPHERIC SCATTERING

This section further analyses the effects of the radiative coupling between surface reflectance and atmospheric scattering. The solid green line on Fig. 2 shows the AF surface BRF in the principal plane for a sun zenith angle (SZA) of 50°. Unlike aerosol particles, land surface tends to generate more backward scattering than forward one.

Figure 2: Effects of scattering optical thickness on the surface BOA BRF field in the principal plane at 320nm. Negative viewing angles correspond to backward direction.
Let us examine now the change in the surface BRF field when an atmosphere is placed on top of the surface, varying the aerosol concentration. In that case, the magnitude of the backward (forward) scattering increases (decreases) as the aerosol optical thickness increases.

As molecular and particle scattering optical thicknesses changes with wavelength (Fig. 3), it is expected that the importance of surface AF BRF smoothing effects due to sky radiation depends on the spectral regions. In other words, the shaping of surface BRF by sky radiation is also wavelength-dependent as illustrated on Fig. 4. In this example, spectrally constant surface BRF intrinsic properties are assumed from 320nm to 750nm. In these conditions, surface BRF shape in the principal plane is invariant in that spectral domain (green line on Fig. 4).

Conversely, the shape of the BOA reflectance is now wavelength dependent. In the ultra-violet region where atmospheric scattering is large due to the high optical thickness (Fig. 3), reflectance anisotropy smoothing by sky radiation is important translating into a surface BRF shape close to a Lambertian one (Fig. 4). At the other end of this spectral region, i.e., at 750nm, sky radiation is pretty low and there is almost no difference between the AF surface reflectance and the BOA one.

Consequently, for a given geometry, BOA surface reflectance exhibits spectral variations within S4 bands even when the surface reflectance intrinsic properties are kept constant (Fig. 5). Two specific geometries in the principal plane have been analysed in detail corresponding to backward and forward directions for a viewing zenith angle (VZA) of 40°. In that case, it can clearly be seen that the AF surface reflectance is spectrally constant in the backward (green line) and forward (orange line) while the corresponding BOA one does exhibit spectral variations. In that specific example, these spectral variations translate into a BOA surface reflectance decrease in the backward direction and a decrease in the forward one as the wavelength increases. Fig. 6 shows the relative difference between the AF surface reflectance and the BOA ones in the two selected geometries. As can be seen, at short wavelength, this difference can exceed +20% in the forward direction (red line) and -10% in the backward one (blue line).

These results show the difficulty to find a simple and unique way to derive a LER value from the knowledge of the AF surface reflectance field. Various ways to relate these two quantities are discussed in the next section.

4. CONVERTING SURFACE BRF TO LER

Four different ways to derive a LER value when the surface AF BRF field in know are discussed.
4.1. LER defined by the AF BRF

The first option presented here consists in setting the value of the surface LER of S4 pixels equal to the AF surface BRF value \( r(\Omega_s(t),\Omega_v; p_i(t)) \) corresponding to the illumination \( \Omega_s(t) \) and viewing condition \( \Omega_v \) at the time \( t \) of acquisition (Eq. 1).

\[
LER(t) = r(\Omega_s(t),\Omega_v; p_i(t))
\]  

The corresponding angular configuration is illustrated on Fig. (7). Eq. (1) assumes that the incoming radiation has not interacted with the atmosphere. Such approximation might hold in the NIR spectral region where the scattering optical thickness is usually low as can be seen on Fig (3). It is however not recommended to apply Eq. (1) in the UV spectral region.

![Figure 7: Definition of the AF surface BRF which depends on the illumination direction \( \Omega_s \) (red line) and viewing direction \( \Omega_v \) (blue line).](image)

4.2. LER defined by the DHR

In the second option, the surface LER value is defined as the Directional Hemispherical Reflectance (DHR) or black-sky albedo defined by Eq. (2).

\[
LER(t) = \frac{1}{\pi} \int_0^{2\pi} r(\Omega_s(t),\Omega_v; p_i(t)) \, d\Omega_v
\]  

As in the previous option described in Section (4.1), no interaction between the incident radiation and the atmosphere is assumed. In the present case, instead of accounting only for the AF BRF value in the S4 viewing direction \( \Omega_s \), the BRF values are integrated over all possible viewing direction \( \Omega_v \) in the upper hemisphere (Fig. 8).

![Figure 8: Definition of the AF surface DHR which depends on the illumination direction \( \Omega_s \) (red line) and integrate all possible viewing directions \( \Omega_v \) (blue lines).](image)

4.3. LER defined the diffuse BHR

The third proposed option consists in defining the surface LER as the BiHemispherical Reflectance (BHR) or white-sky albedo calculated assuming a perfectly diffuse incoming radiation (Eq. 3). Consequently, BHR does not depend on the actual illumination direction \( \Omega_s(t) \)

\[
LER = \frac{1}{\pi} \int_{2\pi/2}^{2\pi} r(\Omega_s(t),\Omega_v; p_i(t)) \, d\Omega_v \, d\Omega_s
\]  

This configuration is also illustrated on Fig. 9. Under perfectly diffuse illumination conditions, surfaces do not exhibit any shadow anymore and the shape of the surface reflectance is similar to a Lambertian one, i.e., the intensity of the reflected radiation is the same in any viewing directions.

![Figure 9: Definition of the surface diffuse BHR that does not depend on the illumination conditions.](image)

4.4. LER defined by the BOA BRF

The last examined option consists in defining the surface LER as the BOA BRF with

\[
LER(t) = \frac{\int_{2\pi} r(\Omega_s(t),\Omega_v; p_i(t)) \, d\Omega_v \, d\Omega_s}{\int_{2\pi} I^d(\Omega_v; \tau) \, d\Omega_v}
\]  

where \( I^d(\Omega_v; \tau) \) is the downwelling at the surface in the direction \( \Omega_v \). Eq. (4) is illustrated on Fig. 10. As \( I^d(\Omega_v; \tau) \) depends on the total scattering optical thickness \( \tau \), it requires to solve the RTE. Among the
four proposed option, it is the best one but also the most
difficult to put in place as it also requires the knowledge
of $I^i (\Omega_s; \tau)$.

Figure 10: Definition of the BOA BRF.

5. DISCUSSION AND CONCLUSIONS

Surface BRF models are used to characterise the
anisotropy of the surface reflectance. This paper
examines possible ways to define a surface LER when
the AF BRF is known. Four options have been
discussed: (i) the LER is set equal to the surface AF
BRF value corresponding to the illumination and
viewing directions which is recommended when the
scattering optical thickness is low, e.g., in the NIR
spectral region; (ii) LER is set equal to the surface DHR
(black sky albedo) of the processed pixel illumination
geometry but this option is not recommended; (iii) LER
is set equal to the surface diffuse BHR (white sky
albedo) which is recommended when the scattering
optical thickness is very large e.g., in the UV spectral
region; and (iv) LER is set equal to the BOA BRF
which is the best recommended choice thought it
requires a detailed knowledge of the downward
irradiance field at the surface.

A proper coupling between surface anisotropy and
atmospheric scattering remains however the best way to
accurately account for the effects of the surface
reflectance on the observed radiance field from
satellites. Pre-computed solutions of the RTE stored in
LUTs are a common way to speed-up retrieval
processes. However, when the anisotropy of the surface
is accounted for, the size of these LUTs might become
prohibitive, as it is necessary to increase the number of
dimensions to accommodate the number of parameters
$p_i$ of the BRF model for different values of scattering
optical thicknesses.

Further efforts are thus needed to analyse ways to
reduce the size of these LUTs while accounting for the
anisotropy of the surface reflectance. Finally, it should
be stressed once again that the characterisation of the
BOA BRF requires the knowledge of the scattering
optical thickness.

6. ACKNOWLEDGMENTS

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