Physics of AnisView

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1. Introduction

All remote sensing measurements acquired in space from space-borne imaging sensors in the solar domain turn out to be strongly dependent on the particular geometry of illumination and observation at the time these measurements are made. In other words, if the same geophysical environment had been observed from a different direction or if the Sun had been at a different location relative to the target of interest, the measurements would have been different. The proper interpretation of such observations must therefore take this variability into account.

A similar situation occurs in the spectral domain: different measurements are acquired when a target is observed in different spectral bands, and this variability is considered as a 'signature' that betrays the nature of the target. The interpretation of remote sensing measurements without understanding the spectral nature of the signals would lead to unrealistic and most probably erroneous results. In the same way, interpreting remote sensing measurements without understanding their directional nature can only lead to inaccurate or useless results.

The reflectance of a geophysical medium is thus dependent on both the direction of the Sun and the direction of the observer with respect to the target. Such a medium is called 'anisotropic', and the reflectance is characterized as 'bidirectional'. By contrast, a perfectly reflecting, non-absorbing surface, i.e., a system that would reflect light equally in all directions, is called Lambertian (or isotropic if some absorption is allowed).

The fundamental mathematical concept describing this anisotropic reflectance is the so-called Bidirectional Reflectance Distribution Function (BRDF). Because it is a distribution (in the proper statistical meaning of the word), it cannot be measured. Indeed, all real sources of light, and all actual instruments have finite dimensions. As a result, the measurements are actually 'hemispheric conical': the target of interest is illuminated by solar radiation coming from the entire hemisphere above the target (often called direct and diffuse radiation), and the light beam collected by the instrument is nominally coming from a small solid angle defined by the center of the target observed and the size of the detector.

For practical reasons (in particular for relative calibration purposes), the measured reflectance of a target is often normalized by the reflectance of a reference panel that is as close as possible to a Lambertian surface, illuminated and observed under identical geometrical conditions. The result of this normalization is then called a bidirectional reflectance factor (BRF).

A large panoply of models have been designed to describe the anisotropy of natural and man-made targets, including vegetation and soils, lakes and oceans, roofs and roads, ice and snow, as well as the many different atmospheric constituents that simultaneously affect the measurements, such as clouds and aerosols. Physically-based models attempt to explain the measured reflectance on the basis of the physical laws describing how solar light interacts with the elements of the environment. They are most useful to express our current understanding of the processes at work, or to get the most accurate results, but they can be very expensive to operate (in terms of their computer resource requirements).

In some cases, users need to be able to represent the shape of the BRF field only, but do not need to retrieve a physical description of the underlying processes. The computation of the albedo of a surface, for instance, requires the knowledge of the variability of the bidirectional reflectance but not necessarily of the causes for that variability. In such occasions, it is appropriate to use a computationally efficient parametric model capable of describing the shape and features of the BRF field in terms of a simple mathematical formula using as few parameters as possible. The RPV and MRPV models fall in that category.

The purpose of this software tool is to demonstrate how the shape of the BRF field changes as a function of the values of the parameters used by the RPV and MRPV models, and to help newcomers in this field with the concepts of bidirectionality and their impact on remote sensing measurements.

2. Outline of the RPV model

The label 'RPV' stands for 'Rahman, Pinty and Verstraete', after the names of the authors of the original publication on this model (Rahman et al. 1993). The basic idea behind this model is to provide as simple as possible a description of the general shape and main features of the anisotropic reflectance field of an arbitrary geophysical medium.

This model has a long history, rooted in astrophysics. Oepik proposed an initial formulation as early as the start of the 20th century. His suggestion was later improved by Minnaert in 1941, who imposed that the formula should verify the reciprocity principle. That formula has long been used to describe the reflectance of planetary surfaces, for instance.

The RPV model is a further development of those initial formulae, and is built as a product of simple mathematical functions, each using one new parameter. Symbolically:

$$BRF = f_0 \times f_1 \times f_2 \times f_3 \qquad (1)$$

where

- BRF is the simulated bidirectional reflectance factor, i.e., the estimate of a particular measurement,
- f_0 is the model parameter that regulates the overall reflectance level,
- f_1 is a function that allows the representation of bowl-shape or bell-shape fields (see below),
- f_2 permits to preferentially increase the reflectance in the forward or backward directions (like for aerosols and vegetation, respectively), and
- f_3 is an optional function allowing the modification of the reflectance in the backward direction (the so-called hot spot).

The analytical formulae for each of these functions is as follows:

$$f_0 = \rho \tag{2}$$

where ρ is the first model parameter,

$$f_1 = \frac{\cos^{k-1}\theta_0 \cos^{k-1}\theta}{\left(\cos\theta_0 + \cos\theta\right)^{1-k}} \tag{3}$$

where θ_0 and θ are the zenith angles of the illumination and observation directions, respectively, and k is the second model parameter,

$$f_2 = \frac{1-\Theta_{HG}^2}{\left[1+2\Theta_{HG}\cos g + \Theta_{HG}^2\right]^{3/2}} \tag{4}$$

is the well-known Henyey-Greenstein phase function and Θ_{HG} represents the third model parameter. Finally,

$$f_3 = 1 + R\left(G\right) = 1 + \frac{1-\rho_{HS}}{1+G} \tag{5}$$

is the function that allows the representation of a local hot spot where ρ_{HS} is an optional fourth parameter to improve the model performance in the hot spot region. In most cases, it is sufficient to impose that $\rho_{HS} = \rho$. Setting ρ_{HS} to values smaller than ρ will increase the hot spot, while larger values will decrease it. In these equations, the following geometrical relations apply:

$$G = \left[\tan^2\theta_0 + \tan^2\theta + 2\tan\theta_0 \tan\theta \cos\left(\phi_1 - \phi_2\right)\right]^{1/2} \tag{6}$$

and

$$\cos g = \cos\theta_0 \cos\theta + \sin\theta_0 \sin\theta \cos\left(\phi_1 - \phi_2\right) \tag{7}$$

where ϕ_1 and ϕ_2 are the illumination and observation azimuth angles, and g is the scattering angle, i.e., the angle between the vectorial directions of illumination (from Sun to target) and observation (from target to sensor). Hence, $g = 0^\circ$ for forward and $g = 180^\circ$ for backward scattering.

The general effect of each function is easily explained and visualized with AnisView:

- f_0, also known as the amplitude factor ρ, is a linear multiplier to the rest of the model, and therefore directly affects the overall reflectance level. If you only change the value of that parameter in AnisView, the shape of the function should remain identical, but the level should be adjusted.

- f_1 is a function of a parameter traditionally labeled the Minnaert parameter k. Generally speaking, values of k less than 1.0 are associated with bowl-shaped BRF distributions, where the bidirectional reflectance increases with the illumination and observation zenith angles. This is the most commonly observed situation in nature for reasonably homogeneous environments. Values of k larger than 1.0, on the other hand, tend to generate bell-shaped reflectance distributions, where the BRF decreases with increases in these zenith angles. This can be verified with AnisView by moving the cursor setting the numerical value of k. Geophysical situations that lead to such bell-shaped reflectance fields ($k > 1.0$) often include sparsely distributed absorbing vertical structures located over much brighter background surfaces. Examples include pine trees over dry soil or snow.

- f_2 is a function which accentuates the relative weight, so to speak, of the forward and backward scattering. In the RPV model, this function is implemented as the well-known Henyey-Greenstein phase function, which enhances forward scattering when its parameter Θ_{HG} takes on positive values, and backward scattering when this parameter becomes negative. In the MRPV model, the parameter b_M behaves similarly. Again, these tendencies can be experienced directly by modifying the appropriate parameter and visualizing the effect.

- Finally, f_3 is the function that allows a local increase of reflectance in the hot spot region. A properly formed hotspot cannot occur when the geophysical system is fully reflecting or totally absorbing. By default, it parameterizes this effect using the same value as f_0 (or ρ), but that can be changed manually by setting a separate hot spot parameter value different from ρ.

3. Outline of the MRPV model

As it turns out, the RPV model is capable of accurately representing the general anisotropy of a wide range of geophysical systems. From a numerical point of view, however, the use of the Henyey-Greenstein phase function creates a difficulty, because this non-linear formula cannot be inverted analytically. Such an inversion can always be achieved numerically, but that can be costly, as it has to be done iteratively.

The MRPV model is a modified version of the RPV model where the function f_2 is replaced by a new function, say $f_2^{'}$, that implements a negative exponential formula instead of the traditional Henyey-Greenstein phase function. This new parameterization, suggested initially by John Martonchik of the NASA Jet Propulsion Laboratory in Pasadena, therefore replaces Equation (4) above by the following:

$$f_2^{'} = \exp\left(-b_M \cos g\right) \tag{8}$$

where b_M is the MRPV model parameter that replaces Θ_{HG} in RPV. This new formulation was first published by Engelsen et al. (1996).

This substitution significantly accelerates the computations, especially in inverse mode, because the new model is now the product of 4 simple factors. The logarithm of the model is thus a sum, and the inversion of such a model against the logarithm of the measurements can be achieved quickly and efficiently without any need for iteration:

$$\ln BRF = \ln \rho + (k-1)\ln\left[\cos\theta_0 \cos\theta\left(\cos\theta_0 + \cos\theta\right)\right] - b_M \cos g + \ln\left(1 + \frac{1-\rho_{HS}}{1+G}\right) \tag{9}$$

Hence, in operational contexts where lots of data need to be processed, or whenever speed of computation is essential, this is the preferred model version to use.

4. References

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