Bidirectional Reflectance Distribution Function (BRDF) of Snow: Corrections for the Lambertian Assumption in Remote Sensing Applications

Wei Li[a], Knut Stamnes[a], Hans Eide[a], and Robert Spurr[b]

[a]*Light and Life Laboratory, Stevens Institute of Technology, Hoboken, New Jersey 07030, USA.* [b]*RT SOLUTIONS Inc., Cambridge, MA 02138, USA*

SUMMARY

For remote sensing over snow-covered surfaces, the bidirectional reflectance distribution function (BRDF) of snow plays an important role that should be considered in inverse algorithms for the retrieval of snow properties. However, to simplify retrievals, **many researchers assume that snow is a Lambertian reflector**. This "forward model" error affects the accuracy of retrieved snow parameters (such as albedo, grain size, impurity).

To rectify this error, we provide a **simple yet accurate semi-empirical correction formula**.

Advantages:

- Easy conversion of top-of-the-atmosphere (TOA) reflectance arising from an anisotropically reflecting snow surface to an equivalent TOA reflectance for a Lambertian surface.
- Translation of TOA radiance computed with the Lambertian assumption into a more realistic value based on a BRDF treatment.
- For the first 8 channels of the VIIRS spectrometer, the R-square regression coefficient for fitting this correction formula is better than 0.95 for a wide range of sun-satellite geometries.

A simple LUT-based interpolation program is provided to allow the user to extract TOA reflectances for any sun-satellite geometry by quick interpolation in the LUTs.

The Lambertian Equivalent Reflectivity (LER) formulation

For a Lambertian surface with albedo ρ_{sur}, the total TOA reflectance, $\rho_{tot,L}(\theta,\theta_0,\Delta\phi)$ in direction $(\theta,\Delta\phi)$, where θ_0 is solar zenith angle, θ the polar angle, and $\Delta\phi$ the relative azimuth angle, can be expressed algebraically as:

$$\rho_{tot,L}(\theta,-\theta_0,\Delta\phi)=\rho_{atm}(\theta,-\theta_0,\Delta\phi)+\frac{\rho_{sur}\mathcal{T}(-\theta_0,-2\pi)\tilde{\mathcal{T}}(\theta,+2\pi)}{\pi[1-\bar{\tilde{\rho}}\rho_{sur}]}. \qquad (1)$$

Here $\rho_{atm}(\theta,\theta_0,\Delta\phi)$ is the TOA reflectance for a nonreflecting surface. Thus, for a Lambertian surface, we only have to solve one radiative transfer problem for a nonreflecting lower boundary; the solution will include the reflectance ρ_{atm}, along with the flux transmittances $\mathcal{T}$ and $\tilde{\mathcal{T}}$ and the spherical albedo $\bar{\tilde{\rho}}$. Clearly, the reason that the Lambertian assumption is so attractive is that an analytic adjustment (second term on the right hand side in the equation above) allows us to find the solutions for any Lambertian reflecting surfaces.

In order to enhance the accuracy of retrieval algorithms based on the Lambertian approximation, we define the correction factor:

$$f_{corr}(\theta,-\theta_0,\Delta\phi)\equiv\frac{\rho_{accur}(\theta,-\theta_0,\Delta\phi)}{\rho_{tot,L}(\theta,-\theta_0,\Delta\phi)}. \qquad (2)$$

To compute the reflectance $\rho_{accur}(\theta,-\theta_0,\Delta\phi)$, we use the coupled atmosphere-snow radiative transfer model DISORT (Discrete-Ordinate Radiative Transfer). The snow pack is treated as a number of additional scattering layers interfaced to the atmosphere; snow optical properties are characterized in terms of grain size and impurity concentration. In this study, we use 54 different snow surface types (8 snow grain sizes: 50, 100 200, 500, 1000 and 2000 μm, and 9 snow impurities: 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 1.5, 2.0, and 2.5 ppmw (parts per million by weight). In the atmosphere, we consider 16 aerosol scenarios which are 2 aerosol models: "Arctic winter model with RH = 50%" and "Average continental model with RH = 99%" and 8 optical depths: $\tau_{865}=0.05, 0.08, 0.1, 0.15, 0.2, 0.3, 0.5, 0.8$. These two models represent extreme opposite cases; it is implicit that the behavior of other aerosol models lies between these two cases. Because of the high albedo of snow surfaces, the influence of aerosols on the correction is not very strong, especially for wavelengths shorter than 0.865 μm.

Errors in the Surface BRDF and the TOA Reflectance

In order to quantify the errors incurred by invoking the Lambertian assumption in the VIIRS snow property retrieval, we start by computing snow surface BRDFs and TOA reflectances for both the Lambertian case and the more realistic snowpack with the same albedo. We then compute the relative errors in the snow-surface BRDFs and TOA reflectances (see Fig. 1). Also, we show the TOA reflectances for VIIRS channels 488, 865, and 1610 nm in Fig.2. These results show that the anisotropy increases with wavelength, but the reflectances are correspondingly smaller. In visible, althrough the relative error is only about 10% - 20%, because the reflectance is 0.8 - 0.9, this error is significant. We have to correct it. In the NIR, the refelctance is less than 0.08. Thus, the relative error is amplified by dividing by this small value.

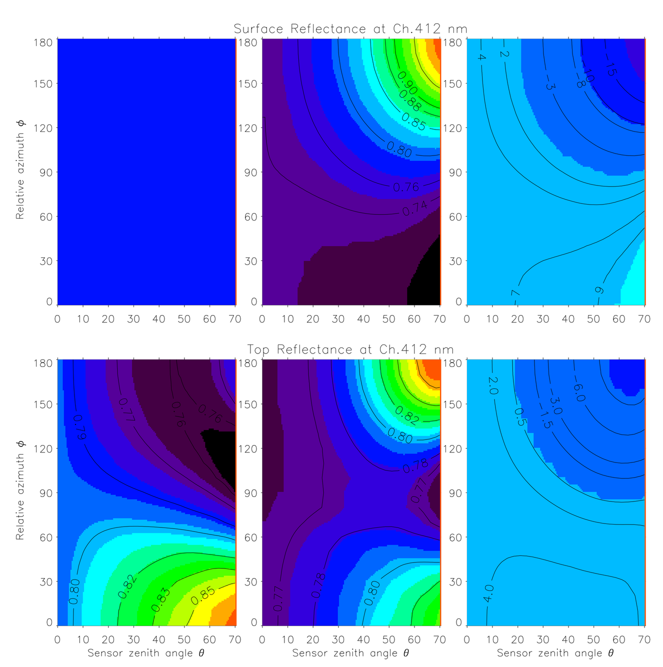

FIGURE 1: Snow-surface BRDF results (upper panels), and TOA reflectances (lower panels). Left panels: Lambertian surface assumption. Middle panels: snow-pack surface. Right panels: Relative error.

There is a nearly linear relationship between the TOA BRDF and the surface albedo (See Fig.3 left panel), because for a snow surface, the albedo always larger than ρ_{atm}, especially in the visible. This behavior implies that it is possible to correct the Lambertian results for anisotropy effects. The factor f_{corr} is shown as a function of albedo in the right panel of Fig.3. There is a very clear relationship between the TOA reflectance ratio or correction factor f_{corr} and the surface albedo, especially at shorter wavelengths. Fig. 3 is for one particular sun-satellite geometry, but the results for other geometries are similar.

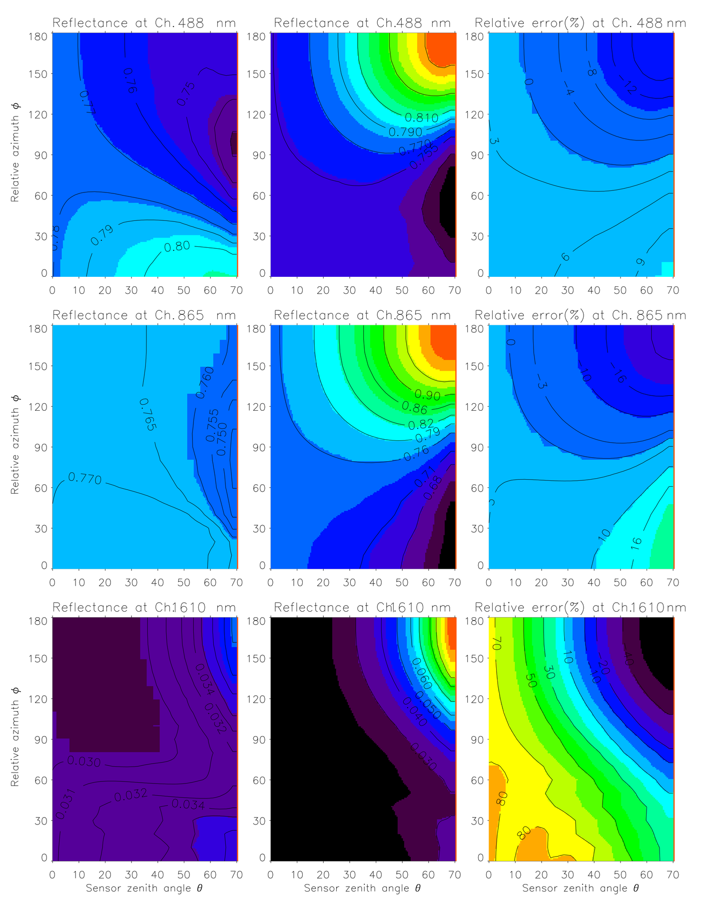

FIGURE 2: TOA reflectances for VIIRS channels λ = 488, 865, 1610 nm. Left panels: Lambertian surface assumption. Middle panels: snow-pack surface. Right panels: Relative error.

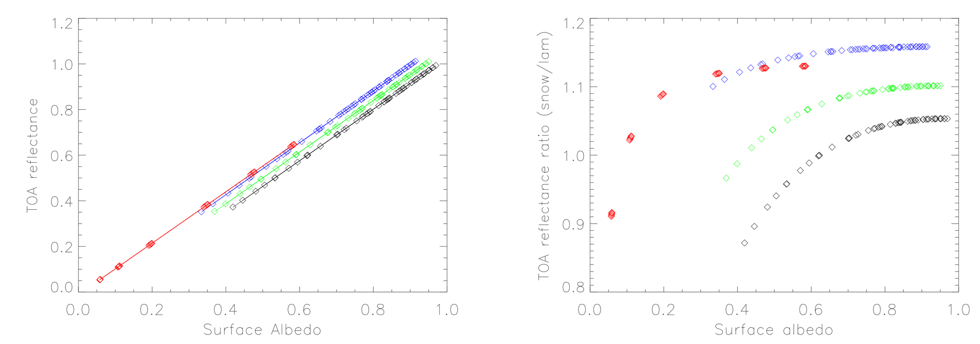

FIGURE 3: Left: TOA reflectance versus snow surface albedo for 54 snow-pack albedo values; Right: The correction $f_{corr}(\theta,-\theta_0,\Delta\phi)$ [Eq. 2]. For wavelengths λ = 412, 488, 672, 1240 nm (black, green, blue, red).

TOA Reflectance Correction

To quantify the dependence on surface albedo and aerosol loading, we consider 54 different snow surface types and perform TOA reflectance calculations for 16 aerosol scenarios. From this sample set of 864 cases, we have found that the following function:

$$f_{corr}(\theta,-\theta_0,\Delta\phi)\approx a_0+a_1\log(\rho_{sur})+a_2\log^2(\rho_{sur})+a_3\log(\rho_{atm}) \qquad (3)$$

provides a good fit to the correction factor as a function of ρ_{sur} and ρ_{atm}.

Table 1. LER correction factor: fitting coefficients and R-square values

VIIRS channel	a_0	a_1	a_2	a_3	R-square
M1 (412nm)	1.52509	2.19848	1.44723	0.243399	0.999983
M2 (445nm)	1.55147	2.22754	1.31316	0.171194	0.999977
M3 (488nm)	1.58534	2.24910	1.16869	0.0989433	0.999970
M4 (555nm)	1.65735	2.28467	0.982694	-0.00294513	0.999966
M5 (672nm)	1.58002	2.24865	0.881272	-0.116735	0.999953
M7 (865nm)	1.51204	2.23637	0.837360	-0.254339	0.999950
M8 (1240nm)	2.88564	2.32828	0.402950	-0.0678523	0.996025
M10 (1610nm)	4.63909	2.75975	0.516396	0.266470	0.975311
M11 (2250nm)	4.78687	2.75306	0.488038	0.240490	0.974284

Table 1 shows the fitting result for one particular sun-satellite geometry (Solar zenith angle $\theta_0=45°$, sensor zenith angle $\theta=30°$, relative azimuth $\Delta\phi=120°$).

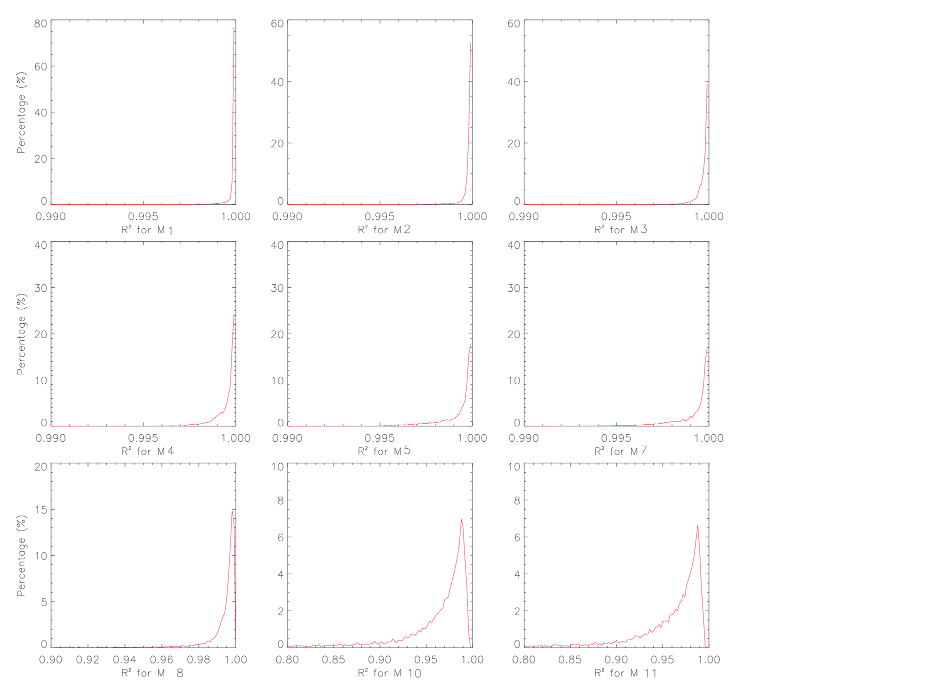

FIGURE 4: Distribution of the regression R-square for the fitting of f_{corr} in the nine VIIRS spectral channels as indicated. Note that the scale on the horizontal axis is not the same in all panels.

To evaluate the accuracy of our LUT results, we display in Fig. 4 the distribution of the regression R-square for all sun-satellite geometries at each VIIRS channel. The R-square values for channels M1 - M8 are better than 0.95, and better than 0.80 for channels M10 and M11.

Reference:

Li, W., K. Stamnes, H. Eide, and R. J. Spurr, Bidirectional Reflectance Distribution Function (BRDF) of Snow: Corrections for the Lambertian Assumption in Remote Sensing Applications, in press, Opt. Eng., 2006.